Optimized Traffic Scheduling And Routing In Smart Home Networks

by

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FOREWORD

This dissertation is submitted for the degree of Doctor of Philosophy at the University of Quebec, Ecole de Technologie Superieure (ETS). The research described herein was conducted under the supervision of Professor Mohamed Cheriet in the Department of Automated Production Engineering and Professor Kim-Khoa Nguyen in the Department of Electical Engineering, between September 2015 and August 2019.

This work is to the best of my knowledge original, except where acknowledgements and references are made to previous work. Neither this, nor any substantially similar dissertation has been or is being submitted for any other degree, diploma or other qualification at any other university.

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2. Attia, Maroua Ben, Kim-Khoa Nguyen, and Mohamed Cheriet. "Dynamic QoS-aware Queuing for Heterogeneous Traffic in Smart Home," 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC 2019 QoS and QoE Workshop), Tangier, Morocco, 2019, pp. 1287-1292. doi: 10.1109/IWCMC.2019.8766750
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Maroua BEN ATTIA

Ordonnancement et routage optimisés du trafic dans les réseaux de la maison intelligente

Maroua BEN ATTIA

RÉSUMÉ

Les réseaux de la maison évoluent rapidement pour inclure un accès physique hétérogène et un grand nombre de périphériques intelligents générant différents types de trafic avec des distributions différentes et des exigences en qualité de service (QoS) différentes. En raison de leurs architectures particulières, très denses et très dynamiques la solution traditionnelle du plus court chemin pour une seul paire de nœuds du réseau n'est plus efficace pour gérer les contraintes de routage entre les réseaux des maisons intelligentes (inter-SHNs) telles que le délai, la perte de paquets et la bande passante dans le réseau hétérogène et entre toutes les paires du nœuds. En outre, les méthodes d'ordonnancement basées sur la qualité de service actuelle prennent en compte uniquement les métriques de priorité conventionnelles basées sur le champ Type de service (ToS) de IP pour prendre des décisions relatives à l'allocation de la bande passante. Ces méthodes d'ordonnancement basées sur les priorités ne sont pas optimales pour fournir à la fois la qualité de service et la qualité d'expérience, en particulier pour les applications de la maison intelligente, car le trafic à priorité élevée ne nécessite pas nécessairement un délai plus strict que le trafic à priorité plus basse. De plus, la fluctuation des distributions de trafic réseau entraîne des trafics concurrents et les méthodes d'ordonnancement actuelles basées sur la qualité de service dans les réseaux de maison intelligente (intra-SHN) ne prennent pas en compte le trafic concurrent dans leurs solutions. Ainsi, le but de cette thèse est de construire un mécanisme de routage efficace, hétérogène et multi-contraintes et un outil d'ordonnancement du trafic optimisé afin de maintenir une communication efficace et à moindre coût entre tous les appareils filaires-sans fil connectés au réseaux des maisons intelligentes et pour traiter efficacement le trafic concurrent et non-concurrent dans SHN. Cela aidera les fournisseurs de services Internet (ISP) et les utilisateurs à domicile à améliorer la QoS et la QoE de leurs applications tout en maintenant une communication pertinente dans inter-SHN et intra-SHN.

Pour atteindre cet objectif, notre cadre de travail doit traiter trois questions clés, qui sont résumées comme suit: i) comment créer un mécanisme de routage à un coût optimal dans les inter-SHNs hétérogènes ? ii) comment ordonnancer efficacement le trafic multi-sources dans intra-SHN basé sur QoS et QoE ? et iii) comment concevoir un modèle de file d'attente optimisé pour les trafics concurrents dans intra-SHN tout en tenant en compte leurs exigences en matière de QoS?

Dans le cadre de nos contributions pour résoudre le premier problème souligné ci-dessus, nous présentons un cadre analytique permettant d'optimiser de manière dynamique les flux de données entre les réseaux des maisons à l'aide d'un réseau défini par logiciel (SDN). Nous formulons un problème d'optimisation de routage basé sur la qualité de service en tant que problème de chemin le plus court sous contraintes, puis proposons une solution optimisée (QASDN) pour déterminer le coût minimal entre toutes les paires de nœuds du réseau, en tenant compte des différents types d'accès physiques et des modèles d'utilisation du réseau.

Pour résoudre le deuxième problème et résoudre les écarts entre QoS et QoE, nous proposons un nouveau modèle de mise en file d'attente pour le trafic de paire de QoS avec des distributions d'arrivées mixtes dans le réseau de la maison intelligente (QP-SH) pour prendre une décision d'ordonnancement dynamique qui considére la QoS et répond aux exigences de délai de tout le trafic tout en préservant leur nature cruciale. Une nouvelle métrique combinant le champ ToS et le nombre maximal de paquets pouvant être traités par le system pendant le délai maximal requis, est définie.

Enfin, dans le cadre de notre contribution au troisième problème, nous présentons un modèle analytique pour une optimisation de l'ordonnancement prenant en compte la qualité de service des trafics concurrents de réseau de la maison intelligente avec des distributions d'arrivée mixtes et en utilisant des disciplines probabilistes de la file d'attente. Nous formulons un problème d'ordonnancement hybride prenant en compte la qualité de service pour les trafics concurrents dans le réseau de la maison intelligente, proposons un modèle de file d'attente innovant (QC-SH) basé sur le modèle économique de la vente aux enchères de la théorie des jeux pour fournir un accès multiple équitable sur différents canaux/ports de communication, et concevoir un modèle applicable pour mettre en œuvre le jeu de vente aux enchères dans les deux côtés; les sources de trafic et la passerelle domestique, sans modifier la structure de la norme IEEE 802.11.

Les résultats de notre travail offrent aux inter-SHNs et aux intra-SHNs un transfert de données plus efficace entre tous les périphériques connectés au réseau hétérogène avec une utilisation optimale des ressources, un traitement dynamique du trafic basé sur QoS/QoE dans SHN ainsi qu'un modèle innovant pour optimiser l'ordonnancement du trafic concurrent de la SHN avec une stratégie d'équité améliorée. Les résultats numériques montrent une amélioration jusqu'à 90% pour l'utilisation des ressources du réseau, 77% pour la bande passante, 40% pour l'ordonnancement avec QoS et QoE et 57% pour le délai d'ordonanacement du trafic concurrents en utilisant nos solutions proposées par rapport aux méthodes traditionnelles.

Mots-clés: Maison intelligente, Qualité de services dynamique, Optimisation de routage, SDN, Qualité d'expérience, Optimisation d'ordonnancement du trafic, Trafic concurrent, théorie des jeux

Optimized Traffic Scheduling And Routing In Smart Home Networks

Maroua BEN ATTIA

ABSTRACT

Home networks are evolving rapidly to include heterogeneous physical access and a large number of smart devices that generate different types of traffic with different distributions and different Quality of Service (QoS) requirements. Due to their particular architectures, which are very dense and very dynamic, the traditional one-pair-node shortest path solution is no longer efficient to handle inter-smart home networks (inter-SHNs) routing constraints such as delay, packet loss, and bandwidth in all-pair node heterogenous links. In addition, Current QoS-aware scheduling methods consider only the conventional priority metrics based on the IP Type of Service (ToS) field to make decisions for bandwidth allocation. Such priority-based scheduling methods are not optimal to provide both QoS and Quality of Experience (QoE), especially for smart home applications, since higher priority traffic does not necessarily require higher stringent delay than lower-priority traffic. Moreover, current QoS-aware scheduling methods in the intra-smart home network (intra-SHN) do not consider concurrent traffic caused by the fluctuation of intra-SH network traffic distributions. Thus, the goal of this dissertation is to build an efficient heterogenous multi-constrained routing mechanism and an optimized traffic scheduling tool in order to maintain a cost-effective communication between all wired-wireless connected devices in inter-SHNs and to effectively process concurrent and non-concurrent traffic in intra-SHN. This will help Internet service providers (ISPs) and home user to enhance the overall QoS and QoE of their applications while maintaining a relevant communication in both inter-SHNs and intra-SHN.

In order to meet this goal, three key issues are required to be addressed in our framework and are summarized as follows: i) how to build a cost-effective routing mechanism in heterogonous inter-SHNs ? ii) how to efficiently schedule the multi-sourced intra-SHN traffic based on both QoS and QoE ? and iii) how to design an optimized queuing model for intra-SHN concurrent traffics while considering their QoS requirements?

As part of our contributions to solve the first problem highlighted above, we present an analytical framework for dynamically optimizing data flows in inter-SHNs using Software-defined networking (SDN). We formulate a QoS-based routing optimization problem as a constrained shortest path problem and then propose an optimized solution (QASDN) to determine minimal cost between all pairs of nodes in the network taking into account the different types of physical accesses and the network utilization patterns.

To address the second issue and to solve the gaps between QoS and QoE, we propose a new queuing model for QoS-level Pair traffic with mixed arrival distributions in Smart Home network (QP-SH) to make a dynamic QoS-aware scheduling decision meeting delay requirements of all traffic while preserving their degrees of criticality. A new metric combining the ToS field and the maximum number of packets that can be processed by the system's service during the maximum required delay, is defined.

Finally, as part of our contribution to address the third issue, we present an analytic model for a QoS-aware scheduling optimization of concurrent intra-SHN traffics with mixed arrival distributions and using probabilistic queuing disciplines. We formulate a hybrid QoS-aware scheduling problem for concurrent traffics in intra-SHN, propose an innovative queuing model (QC-SH) based on the auction economic model of game theory to provide a fair multiple access over different communication channels/ports, and design an applicable model to implement auction game on both sides; traffic sources and the home gateway, without changing the structure of the IEEE 802.11 standard. The results of our work offer SHNs more effective data transfer between all heterogenous connected devices with optimal resource utilization, a dynamic QoS/QoE-aware traffic processing in SHN as well as an innovative model for optimizing concurrent SHN traffic scheduling with enhanced fairness strategy. Numerical results show an improvement up to 90% for network resource utilization, 77% for bandwidth, 40% for scheduling with QoS and QoE and 57% for concurrent traffic scheduling delay using our proposed solutions compared with Traditional methods.

Keywords: Smart home, Dynamic quality of services, Route optimization, SDN, Quality of experience, Traffic scheduling optimization, Concurrent traffic, Game theory

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LIST OF ABREVIATIONS

AP	Access Point
AR	Access Router
BER	Bit Error Rate
CO	Central Office
CBSP	Constraint-Based Shortest Path
CCM	Multi-Channel Concurrency
CDMA	Code Division Multiple Access
DCLC	Delay-Constrained Least-Cost
D2D	Device-to-Device
DiffServ	Differentiated Services
ETS	École de Technologie Supérieure
ECC	Elliptic Curve Cryptography
EH-LARAC	Extended Hybrid LARAC
EHM-LARAC	Extended Hybrid multi-constraints LARAC
FQ	Fair Queuing
FIFO	First in First out
FIFO-prem	FIFO preemptive
ForCES	Forwarding and Control Element Separation
HSN	Heterogeneous Sensor Network

HWSN	Heterogeneous Wireless Sensor Network
H-LARAC	Hybrid LARAC
HPQ	Hybrid Priority Queuing
ICN	Information-Centric Networking
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
Inter-SHN	Inter-Smart Home Network
Intra-SHN	Intra-Smart Home Network
IoT	Internet of Things
ISP	Internet service provider
ILP	Integer Linear Program
IP	Internet Protocol
IntServ	Integrated Services
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LARAC	Lagrangian Relaxation Based Aggregated Cost
LTE	Long Term Evolution
LDPUs	Local Data Processing Units
MAC	Media Access Control
MANETs	Mobile Ad hoc Networks

MMPP	Markov-Modulated Poisson Process
MMPP-2	Binary Markov-Modulated Poisson Process
M2M	Machine-to-machine
MTU	Maximum Transmission Unit
MPLS	Multi-Protocol Label Switching
NSERC	Natural Sciences and Engineering Research Council of Canada
OSPF	Open Shortest Path First
OFTRE	Offline Traffic Redundancy Elimination
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
P-OFTRE	Path-based OFTRE
QoE	Quality of Experience
QoS	Quality of Service
QASDN	QoS-Aware Software-Defined Routing
QP-SH	Queuing model for QoS-level Pair traffic in smart home network
QC-SH	Queuing model for single QoS-level concurrent traffic in the smart home network
RR	Round-Robin
SDN	Software-defined network
SAQR	Simulated Annealing based QoS-aware Routing
SP	Service provider

SCN	Smart Community Network
SHN	Smart Home Network
ToS	Type of Service
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UHD	Ultra-High Definition
VOIP	Voice over Internet Protocol
VANETs	Vehicular Ad hoc Networks
WMSN	Wireless Multimedia Sensor Networks
WFQ	Weighted Fair Queuing
WRR	Weighted Round-Robin
WNAVS	Wireless Network Assisted Video Streaming
WBAN	Wireless Body Area Network

INTRODUCTION

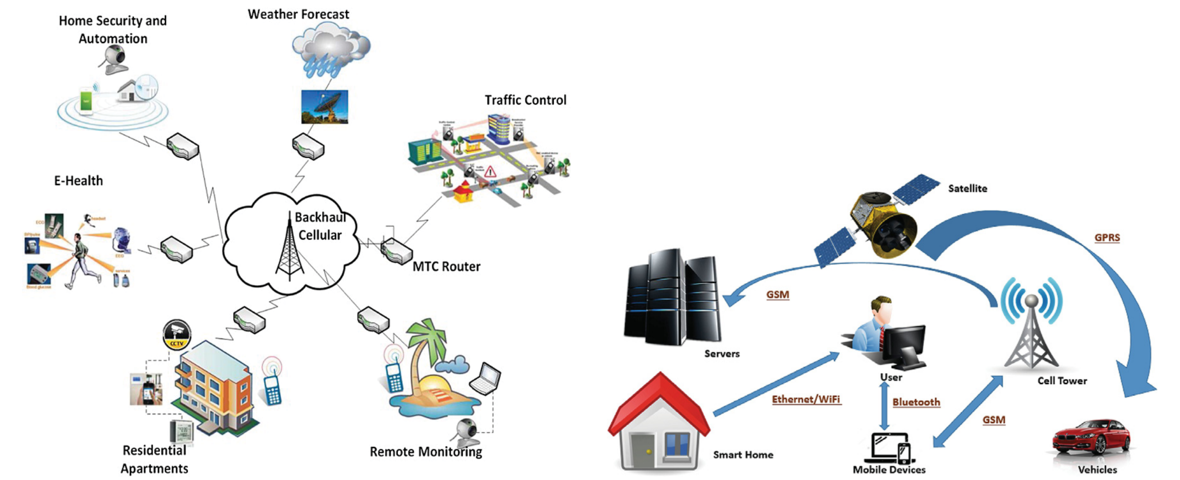
The purpose of this chapter is to present the motivation for the research activities on optimizing smart home networks and to provide a general background about the importance of this topic in the success of future smart home technology.

0.1 Definition and Key concepts

0.1.1 Smart Home Networks

The communicating machines (M2M) have emerged as a state-of-the-art technology for next-generation communication. This technology makes it possible to manage the communication between the connected objects through the ICT networks (Information and Communication Technologies) and without human intervention. It involves creating an automatic exchange of information between devices, machines and systems in a small space of point-to-point communication network to respond to specific tasks using remote control systems via an application, often proprietary software. Several applications have benefited from this technology, including health care, surveillance, smart transportation and smart home.

Unlike M2M technology, Internet of Things (IoT) is a network-wide system where each object, including non-intelligent and static objects, is identified and communicates with a cloud platform. We can consider that IoT is a more extended version of M2M and especially more open since the processing and transmission of information is dematerialized and goes on an Internet scale. IoT induces standardization, common standards in its operation. Most connected objects are for example identified by an IP address, like a computer connected to the Internet. Iot offers large number of smart applications like connected car, industrial Internet, connected health, smart grids and smart city. Fig.0.1 depicts M2M and IoT communication networks.



a) M2M network Hussain *et al.* (2017). b) IoT network Ejaz & Anpalagan (2019).

Figure 0.1 M2M and IoT application network.

Smart home networks can be partitioned as inter-Smart Homes Networks (inter-SHNs) and intra-Smart Home Network (intra-SHN). Inter-SHN are networks that connect home networks to each other and form a Smart Community Network (SCN) which is an IP-based network that creates “a wireless mesh network among citizens, providing a network that is independent, free, and (in some cases) available where regular Internet access is not”Hardes *et al.* (2017). Intra-SHN is an attractive practice of smart community network which is “a multi-hop network of smart homes that are interconnected through radio frequency following wireless communication standards such as WiFi (IEEE 802.11)” Li *et al.* (2011) as well as wired communication standards.

A smart home is any form of residence (for example, a self-contained house, an apartment or a unit in a social housing complex) equipped with special and structured wiring, allowing the owner to remotely control or manage a network of electronic and electrical devices in the home. This network includes sensors, Household appliances, Electronic and multimedia devices. Sensors are devices used to detect the location of people and objects, or to collect data on states (eg, temperature, energy consumption, windows/doors open, movement, broken glass). Household appliances refer to washing machines, refrigerators, etc. Electronic devices include phones, televisions and laptops. Electrical devices refer to toasters, kettles, light bulbs, etc.

The network linking these different devices and technological informations and through which one can operate or access remotely (from outside the home) to all components, is a core network of the smart home concept. The existence of this communication network is essential to distinguish the smart home from a home simply equipped with autonomous high-tech features. Thus, a smart home is identified by these four key aspects that make it different from the traditional home:

- A communication network which allows data transmission among the different home appliances
- Agile controls to manage the home network
- Sensors that gather data
- Smart devices that replay to sensor data or user directions and from the system provider(example, remote management of devices)

With a smart home network, a home can meet the constraints of the network to match supply and demand in a cost-effective manner while meeting the preferences and needs of users. This could be achieved for electricity and heating systems via the automated management of controllable loads. For example, an operationally variable load, such as a washing machine, can be programmed to operate overnight so that the laundry is terminated by a predetermined time while changing the peak demand to avoid local network congestion or contribute to national balancing at the same time.

0.1.2 SHNs controller

Smart home applications and services are becoming more complex and demanding, this requires a rapid evolution of the internet to meet their requirements. The emergence of the concept of "programmable networks" as a means to facilitate the evolution of the network has introduced the new software-defined networks (SDN) paradigm. SDN offers a promising solution for greatly optimizing and simplifying network management, while uncoupling the data layer which contains simple packet transmission devices (which can be programmed via an interface such as OpenFlow) from the network control layer (in which network intelligence is logically centralized). Applying this new concept of networking in the home solves the problem of installing a home gateway with middleware specified for each standard to manage the home network. As a result, additional maintenance and repair costs are eliminated.

Two architectures of SDN exist Nunes *et al.* (2014), that of ForCES (Forwarding and Control Element Separation) Haleplidis *et al.* (2014) and that of OpenFlow Akyildiz *et al.* (2014). Both approaches allow the decoupling of the control layer and the data layer as well as the normalization of information exchange between these two layers. The SDN architecture according to ForCES, presented by the Fig.0.2 considers that control and data plans are kept in close proximity. In contrast, the control plane is completely separated from the network device in OpenFlow's SDN architecture, which is shown in Fig.0.3.

In addition, the transmission model used by ForCES is based on Logical Function Block (LFBS), which allows the controller to configure the transmission devices, while OpenFlow uses flow tables that contain entries each of which determines how packets belonging to a stream will be processed and transmitted.

The "software-defined" feature of the SDN technology allows reconfiguration by enabling administrators to easily collect signals or modify parameters in the packets and to quickly com-

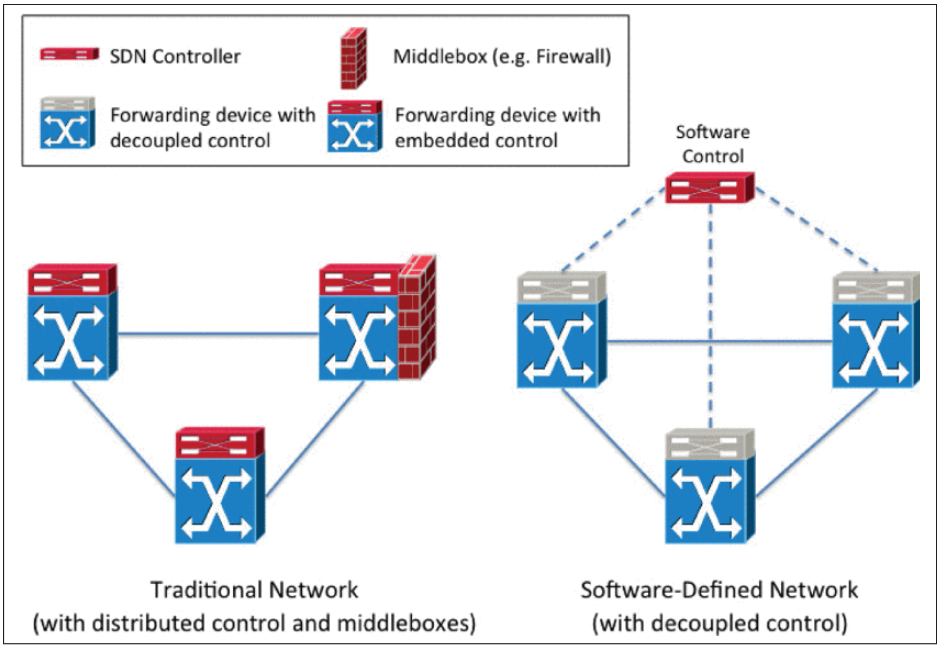


Figure 0.2 SDN architecture according to ForCES Nunes *et al.* (2014).

pute a suitable path. This ultimately leads to a self-adaptive environment that is capable of dealing with both wired and wireless devices from different types. However, with the diversity and complexity of the OpenFlow transmission rules (the coupling flexibility and the diversity of the measures to be taken at the arrival of packets) compared to those in the traditional IP routers, the memory of OpenFlow switches may to be insufficient to handle these tasks. In addition, the latency between the controller and the switch is very important for sizing a network and evaluating its performance. Thus, applying SDN in smart community raises some challenges related to performance and resource management Karakus & Durresi (2017); Han *et al.* (2016); Hassan *et al.* (2017); Rademacher *et al.* (2017).

0.1.3 QoS and QoE in SHNs

The concept of quality of experience (QoE) has emerged in network applications where the quality of service was not enough. The perceptual system of each human presenting specific

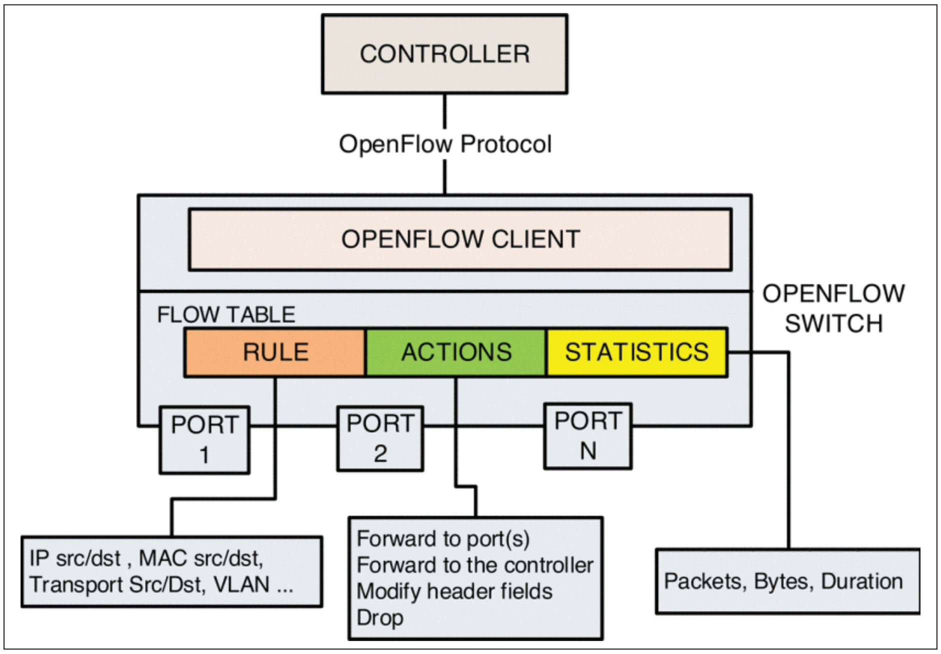


Figure 0.3 SDN architecture according to OpenFlowNunes *et al.* (2014).

sensitivities, a user does not perceive a service in the same way as his peer. Thus, the quality threshold varies from one user to another. This new concept was initially used in communication services. It is determined based the study, design and evaluation of the authenticity of people who use a system as well as by inspecting the content of the service. Thus, the quality of experience presents the degree of pleasure of end-user regarding an application or a service. It results from the fulfillment of its expectations with respect to the utility and enjoyment of the application or service in the light of its personality and its current state.

The quality of service (QoS) is based on both network performance metrics (like delay, bandwidth and packet loss rate) and non-network performance metrics (often related to service contracts associated with the network, such as time-to-recovery and time-to-service). QoS can be classified into two main types: prioritizing and reserving resources. Different solutions can be used, such as differentiation of services (DiffServ), integration of services (IntServ) or "Multi-Protocol Label Switching" (MPLS) Janevski (2019). The concept of QoS has been defined by several organizations including the International Organization for Standardization (ISO) Kilkki & Finley (2019) and the International Telecommunication Union (ITU) Mustofa *et al.* (2018). It is generally related to the low layers of the OSI architecture and associated with technical parameters of the network or the service.

0.2 Context and problem statement

0.2.1 General Context

The application of M2M communication in SHNs is a complex process. Home networks are expanding rapidly to include a multiple physical access (including wired and wireless) and a large number of devices that can generate different types of data. This network is growing rapidly to include many different multimedia devices (such as tablets, smartphones, connected TVs, etc.) all along the arrival of the Internet of Things (IoT) which connects several objects to the cloud (such as sensors, appliances, electronics, etc.). Therefore, the industrial and academic communities have begun to explore ways to better design and manage SHNs. In such dense network environment, there are a variety of application types (VoIP, messaging, video, etc.) with different resource requirements putting more constraints in M2M communications including delay, packet loss, and bandwidth. In a smart community context ("Star ÉTS: A Sustainable Cloud-Based Smart ÉTS Residence" project) and as shown in Fig.0.4, each home has a gateway that will be connected to an external router (ONU) that presents an exit point to the external network. The short distance between two homes makes the home gateway capable of serving more than one home at the same time. Therefore, it will have several possible paths (with different costs) to route packets.

In addition, different physical connections have different advantages and limitations in terms of data capacity, speed, distance, cost, and installation requirements. Therefore, the preferred type of connection will depend on the application or type of service for which it is intended.

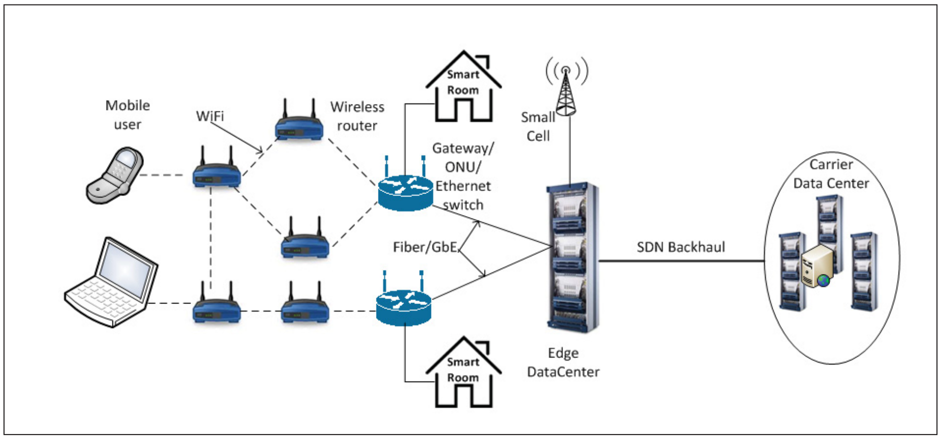


Figure 0.4 Routing in SHNs.

A wide range of communication protocols exists and vary depending on the physical medium with which they are associated. Different networks and protocols are developed by different manufacturers and suppliers, forcing brand loyalty from smart homeowners. As a result, even though ZigBee has emerged as the leading wireless standard, several large companies in the industry support alternative technologies such as WiFi, Z-Wave, 6LoWPAN2 making it difficult to deploy an heterogeneous routing in the inter-SHNs.

Moreover, network devices are generally resource-constrained, which places many constraints on M2M communications, including the cost of computing the best route in terms of cost (short-path problem), delay, storage (routing tables, caching), and bandwidth. Thus, along with the increasing size of the community network, the large volume of data generated by numerous devices producing huge number of cached data in routers will saturate the memory of access points (APs). This produces scalability issues for AP memory size. Information-centric networking (ICN) technology offers a promising solution for optimizing in-network caching by using an Unified Content Name to fetch data by their names, not by host location (through TCP/IP)Inoue & Mizuno (2019). However, ICN caching cannot be applied in both intra-SHN and inter-SHNs because of the nature of their transferred data. In fact, unlike the Internet traffic, SHN traffic includes only IoT data and SH routers are not designed for media transmission

Nour *et al.* (2019). In addition, most of existing ICN-based caching solutions do not consider IoT applications in their deployment design Amadeo *et al.* (2016). ICN technology can be used at the IP-level of the smart community's external traffic.

Furthermore, the rapid increase in latency causes significant QoE deterioration for delay-sensitive applications. For example, high latency for VOIP calls introduces an unacceptable delay into the conversation. In addition, a ping of 200 ms, in online games, will make the game unplayable, and most servers unreachable, which may include a subscription to an additional service other than the subscription for access to data. Also, in a congested route, if several lower priority packets arrive in a short period of time, the length of the queue increases dramatically causing the dropping of higher priority packets that will come later. This requires to consider the priority of the packets in the processing of incoming packets and provide different classes of services to reduce the cost and prevent packet loss. Since smart home gateways have to manage multi-sourced network traffic generated over different network channels/ports, with mixed distributions and with different QoS and QoE requirements, it involves complex dynamic queuing strategies to solve the gaps between QoS and QoE and handle packet concurrency issue.

As shown in Fig.0.5, we partition the overall network as intra-Home and inter-Homes networks, so that we can tackle the problems separately. In order to address intra-Home and inter-Homes network requirements, home gateways and access routers have to drive multiple tasks that shall cover: i) an heterogeneous efficient multi-constrained all-pair nodes routing approach that optimizes the network resource allocation and the total operational cost, ii) a QoS/QoE-aware queuing mechanism that minimizes time and space computational overhead, and iii) a dynamic scheduling solution to fairly process concurrent traffics in order to avoid the unwanted extra delay especially for critical applications. In this thesis, access points and home gateways are controlled by a central controller located in a central office. This controller uses a mechanism to apply the proposed scheduling and routing methods to the smart home access points and gateways as described in Fig.0.5. The control mechanism can be implemented on top of Java/OSGi using JMX as described in Frenot *et al.* (2008), using JFED toolkit Vermeulen *et al.* (2014) based on EmuLab-based experiment management system Lima *et al.* (2019) as in Struye *et al.* (2018) or, using web-based solutions with task synchronization support as in Huang *et al.* (2006). In this thesis, we focus on the scheduling and routing methods used by the controller rather than the communication between the controller and the access points or home gateways.

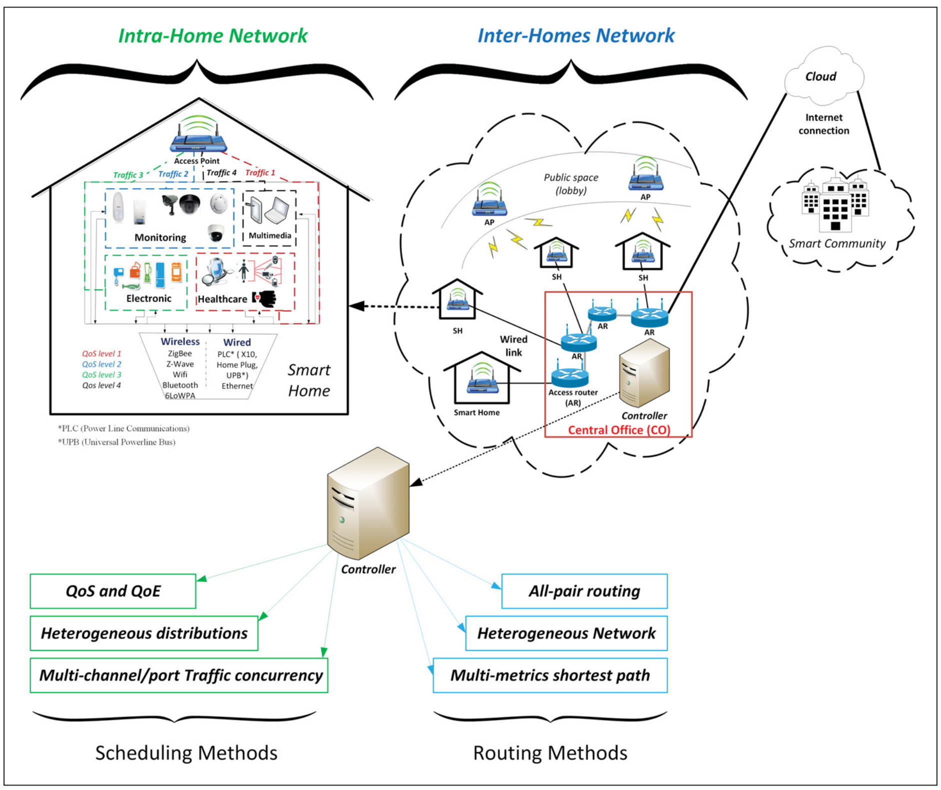


Figure 0.5 General architecture of SHNs.

0.2.1.1 Intra-Home network requirements

The key factors that should be considered in a smart home network are summarized as follows:

0.2.1.1.1 Application type of service

The types of services offered by smart home have to be categorized according to the needs of the users they serve or types of technical applications. A holistic approach reveals a wider range of services such as safety, assisted living, health, entertainment, communication, convenience, comfort, and energy efficiency. These services define the priorities of traffic scheduling task. For example, delay-sensitive application that needs fast response to specific events, requires a prioritized processing. Thus, each packet need to be processed by home gateway based on its type of service: packets with higher priorities are served before those with less priorities. For example, streaming devices (that have video bitrates between 400 kbps and 14,000 kbps IBM (2018)) require a lower maximum delay compared to periodic sensing objects as medical sensors (with sensing rate between 12 bps and 12 kbps).

0.2.1.1.2 Traffic criticality

The type of service metric may reflect the criticality of network applications, however, higher priority traffic do not necessarily require higher stringent delay than lower-priority traffic. For example, fire detector and medical sensor packets are more critical than packets generated from streaming devices and need to be processed quickly to prevent serious property damage or injury since a small fire can rapidly turn fatal and we not always have enough time for safe evacuation.

0.2.1.1.3 The heterogeneous distributions queuing adaptability

Smart home traffics are generated from different network devices and with different distributions according to the type of transferred data and generation process. Data can be generated periodically and sent to a central server (usually on the cloud) the states of monitored devices for each period T (i.e., connected thermostats, network sensors, medical sensors, etc.), by triggering some events (for example, door/window sensors, motion detectors, etc.) to indicate the status of the monitored object or person, or continuously by tablets, connected televisions, surveillance cameras, etc. Thus, smart home network requires an adaptive queuing system to handle the fluctuation of network traffic distributions with mixed arrivals.

0.2.1.1.4 Multi-channel/port traffic concurrency

Since the dynamic nature of today's home network caused by the fluctuation of network traffic distributions has a direct impact on scheduling engines in terms of congestion and packets concurrency, an automated management of traffic loads within the home gateway by offering multiple concurrent access for the same channel/Ethernet port is mandatory. Recent advances in optical, wireless and cellular modulation technologies have been made from the perspective of increasing the number of concurrent users per media access. Unfortunately, these solutions become less effective in delay for multi-channel/port concurrency issue and do not consider the fairness between traffic flows from the same class of service which makes them unsuitable for delay-sensitive applications. Thus, smart home network requires an efficient queuing model to address the multi-channel/port traffic concurrency issue.

0.2.1.2 Inter-Homes network requirements

The key factors that should be considered in inter-SHNs are summarized as follows:

- **All-pair routing**

  Community network topology has a very high density of nodes communicating simultaneously with each other. In this network, all paths between source-destination pair of nodes need to be determined in order to reduce the communication cost of last-mile applications and improve interaction among users in a the inter-SHNs. For example, if an end user wants to share his TV screen with others within an inter-SHN to broadcast news, the shortest paths from his home to all other nodes in the community has to be determined. Another example is public safety: if an illegal penetration is detected in a home, all neighbors must be notified immediately to apply appropriate protections. This requires communication among all pair of nodes to be established dynamically with a highest priority. The high level of cooperation within smart homes imposes new challenges on inter-SHNs management and traffic engineering. Traditional single path end-to-end routing protocols become no longer appropriate.

- **Multi-metrics shortest path**

  Smart community network offers services to a wide range of application like monitoring, health assistance, safety and energy efficiency, which require diverse resources in terms of bandwidth, delay and memory, producing traffics with different Quality of Service (QoS) levels. Moreover, a large number of devices in the community generate a huge volume of data which deteriorates home network QoS in terms of latency and packet loss. Thus multi-metrics have to be considered at the calculation of the shortest path in the inter-SHNs.

- **The reliability of different types of physical accesses**

  Smart community network is a heterogeneous infrastructure made of multiple physical accesses like wired and wireless. Each device uses a different communication technology at the physical level (such as WiFi, 6LoWPAN, Zigbee, Bluetooth, PLC, x10, Ethernet, etc.), at the protocol level (such as Ethernet (multi-node), OpenFlow (SDN), FTTH: Fiber to the Home, etc.) and even at the network level (such as DDP: Datagram Delivery Protocol, IP: Internet Protocol, etc.). This wide variety of communication technologies makes it more difficult to implement a common infrastructure to ensure communication between these devices and the rest of the home network.

0.2.1.3 Motivation

In order to provide success key-requirements for future smart home networks, heterogeneous multi-constrained routing and scheduling approaches need to be efficiently designed and implemented at a lower cost. Wired-wireless communication between all-pair of nodes needs to be established with minimum loss to ensure reliable transmission. Moreover, bandwidth and access point memory have to be taken into account when designing the routing protocol in order to bypass network congestion and avoid extra connection delay. In addition, dynamic queuing model for traffic with mixed arrival distributions need to be developed to enhance network transmission delay. QoS and QoE need to be further optimized using revolutionary priority metrics that ensure delay requirement for each class of traffic while preserving the degree of criticality of the most dangerous/risky home network applications. Furthermore, innovative scheduling tools based on game theory models need to be implemented in such dynamic and dense smart home network to fairly process concurrent traffic over different communication channels/ports caused by the fluctuation of network traffic distributions. The motivation behind the specific routing and scheduling mechanisms proposed for SHNs in this thesis is as follow:

- The short distance between two homes makes the home gateway capable of serving more than one home at the same time. Therefore, all paths between source-destination pair of nodes need to be determined in order to reduce the communication cost of last-mile applications and improve interaction among users in an inter-SHN, while in the general context only single path end-to-end routing protocols are used.
- SHNs are heterogeneous infrastructures made of multiple physical accesses that makes it more difficult to implement a common infrastructure to ensure communication between SH devices and the rest of the home network.

- The specific traffic distribution in smart homes can be classified into three categories, as presented in Section 5.4, while in the general context like the Internet it is normal distribution which is hard to model.
- The packets concurrency model caused by the fluctuation of network traffic distributions can be easily implemented in the home gateway serving a limited number of flows in the home.

As a summary, the efficiency of future smart home networks can be achieved by:

- Designing an efficient routing solution for smart home networks that considers the heterogeneous communication between all-pair of nodes and reduces delay and network transmission cost.
- Defining new network metrics to dynamically schedule multi-sourced smart home traffic while ensuring both QoS and QoE requirements.
- Fairly controlling concurrent traffic over different media accesses and optimizing scheduling delay.

0.2.2 Problem statement and Research questions

The research problem addressed in our work is stated as follows:

PS: How to design and deploy an efficient network control mechanism for future smart home architecture that optimizes routing and queuing system to efficiently reduce resource consumption and meet both QoE and QoS requirements.

In order to address the above problem statement and drive our work methodology that will be discussed in Section 2, we further detail the problem statement into three research questions (RQ) as follows:

0.2.2.1 Research question RQ1

RQ1 (Routing): How to design and implement an optimized routing system in heterogeneous wired-wireless smart home networks? The main issues related to RQ1 are:

- How to determine the minimum cost between all pairs of nodes in smart home networks?
- How to reduce packet loss and minimize the response time?
- How to find the optimal path while minimizing the use of bandwidth?
- How to optimize caching assignment process in order to reduce the memory consumption in network Access Point?

0.2.2.2 Research question RQ2

RQ2 (Scheduling): How to model and deploy an optimized queuing system in heterogeneous smart home traffic ?

The main issues related to RQ2 are:

- How to schedule traffic with mixed arrival distributions in Smart Home network?
- How to optimize queuing decision in order for traffic to meet their QoS and QoE requirements?
- How to define scheduling metric for smart home traffic that ensures their delay requirement and preserves their degrees of criticality?

0.2.2.3 Research question RQ3

RQ3 (Concurrency): How to enhance the resource sharing for concurrent traffic over different communication channels/ports in dynamic smart home network ?

The main issues related to RQ3 are:

- How to fairly schedule concurrent traffic belonging to different media access?
- How to increase the number of concurrent packets that meet their deadline?
- How to reduce the total scheduling delay for concurrent smart home traffic?
- How to implement the QoS-aware scheduling model for concurrent smart home network traffics?

0.3 Outline of the thesis

This introductory chapter defines some key concepts of the thesis, explains the general context and presents the problem statement. Chapter 1 reviews the prior work related to the scope of the research problems. In Chapter 2 the general methodology to address the various research questions of the problem and the objectives of the thesis are mentioned. The resulting thesis diagram for optimizing traffic scheduling and routing in SHNs is then described. Then, the three next chapters present the three articles published in response to the specific research questions. The three articles are outlined as follows:

1. Chapter 3: QoS-Aware Software-Defined Routing in Smart Community Network.
2. Chapter 4: Dynamic QoE/QoS-aware Queuing for Heterogeneous Traffic in Smart Home
3. Chapter 5: Dynamic QoS-aware Scheduling for Concurrent Traffic in Smart Home

Chapter 6 provides a critical discussion of some concepts of the thesis that highlights the strengths and weaknesses of the proposed methods. Finally, the general conclusion summarizes the work presented in this thesis and provides future horizons.

LITERATURE REVIEW

This chapter presents a review of the state-of-the-art methods related to the routing and scheduling optimization problems for inter and intra smart home networks. This chapter is divided into Three (3) sections that are in line with the challenges discussed in the introduction and faced by inter-SHNs (or SCN) and intra-SHN to build and operate future efficient smart network. The first section presents the various routing challenges encountered by SHNs. It presents also the different multi-constrained and heterogeneous routing methods. The second section presents several QoS and QoE-based scheduling approaches. The third section covers the concurrent traffic scheduling solutions.

1.1 QoS-based routing approaches

Different routing protocols have been proposed according to the application or the network architecture.

1.1.1 Heterogeneous routing solutions

1.1.1.1 Central routing solutions based on SDN

Huang *et al.* (2016) used graph theory to solve the throughput maximization problem in SDN. They proposed two algorithms: one for snapshot scenario where requests arrive at the same time, and the other for online scenario where requests arrive one by one. Their solution has shown a good performance for both algorithms in terms of the number of requests, the run time and the quality of solutions delivered. Authors in Amokrane *et al.* (2015) solved the high-energy consumption problem in campus networks, which is formulated as an Integer Linear Program (ILP). They proposed an online per-flow routing algorithm (AC-OFER), in SDN, based on ant colony approach. This algorithm allows dynamic reconfiguration of flow routing and device status by switching off/on network devices and taking into account bandwidth and delay constraints. Their solution reduces more energy consumption than the shortest path routing. Han *et al.* (2016) contributed a QoS-aware routing framework for Wireless Multimedia Sensor Networks (WMSN) in SDN. Their solution, which is based on Open Shortest Path First (OSPF), computes the suitable path meeting QoS requirements for delay-sensitive flows, bandwidth-sensitive flows and best-effort flows.

Lin *et al.* (2017) introduced a QoS-aware routing architecture for SDN switches and legacy switches, which includes a Simulated Annealing based QoS-aware Routing (SAQR) algorithm that uses the Spanning Tree protocol as network discovery mechanism. The proposed SAQR algorithm provides an adaptive tuning for delay variation, loss rate and bandwidth deviation. Egilmez *et al.* (2013) contributed a new QoS architecture based on OpenFlow protocol as well as a priority based dynamic routing optimization framework. Their framework aims at optimizing routing decisions in order to provide QoS (in terms of packet loss and delay variation). The authors apply their framework on QoS-based routing of a video stream with three QoS levels: QoS Level 1 contains dynamically transmitted flows with the highest priority, QoS Level 2 contains dynamically transmitted flow after fixing routes of Level 1, and finally Best-effort contains the flows transmitted by the shortest path (not dynamic). The authors presented the dynamic routing with QoS as a constraint to the shortest path problem. Their solution, based on LARAC optimization, computes the best route that minimizes the cost function (delay variation and packet loss) while keeping delay variation lower or equal to a specified value. The authors showed their framework meets the service level requirements of broadcast video in most cases.

1.1.1.2 Hierarchical routing solutions

most existing hierarchical routing protocol (heterogeneous/homogeneous wireless/wired sensor network routing approaches) mainly focus on reducing energy and increasing network lifetime rather than QoS support like QoS-based routing protocols. Du & Lin (2005) proposed a routing protocol (HSR) for Heterogeneous sensor networks (HSN). The network is composed of a large number of low power nodes and small number of high power nodes. Each low power node sends data to the neighbor that has the shortest distance to the high power node using a greedy routing protocol. Each high power node sends data to the neighbor high power node. In this approach, both types of nodes are static and are uniformly and randomly distributed in the network. The solution shows a good performance in terms of throughput and energy savings, however, it is only based on a single metric (distance) shortest path algorithm; it doesn't consider the capability of each node QoS routing, and the static network topology is not suitable for many applications.

Du *et al.* (2009) contributed a routing protocol for key management based on Elliptic Curve Cryptography (ECC) public key algorithm to enforce security, reduce energy consumption and improve storage requirement for key sharing among low power nodes in HSN. The authors proposed a centralized and distributed approaches for their ECC-based key management scheme. In the centralized approach, each high power node broadcasts the routing structure information to its low power nodes using their public keys and verifies newly-deployed nodes using a special key. In the distributed approach, each high power node generates and signs a certificate to its low power nodes using their MAC and public keys. In this approach, each low power node stores a pair of ECC keys as well as public keys of its high power node. In both approaches, nodes are deployed according to a predefined topological tree structure, however, in the case of an undefined network topology, each low power node will store the public keys of all high power nodes (since it doesn't know its corresponding high power node), this will rise storage and energy issues in low powered nodes as well as security issues.

Another hierarchical structure routing protocol (ERP) is proposed by Bara'a & Khalil (2012). It is aimed to find the optimal number of cluster heads and their locations in a heterogeneous wireless sensor network (HWSN) in order to reduce energy consumption and prolongs the network lifetime (by minimizing the total number of cluster heads) as well as the stability period (by decreasing transmission distance). To this end, they introduced cluster's cohesion metric (which is the sum of the smallest distances between a non-cluster head node and its cluster head node, for all cluster heads in the system), and cluster separation metric (which is the minimum Euclidean distance between any pair of cluster heads in the system). Although this approach improves network lifetime and stability period, it uses an iterative optimization scheme for the selection of the best breed for cluster heads that makes an extra delay and overhead in the setup phase of each network transmission round.

1.1.2 Constrained routing solutions

1.1.2.1 Mono-constrained routing solutions

Guck *et al.* (2017) evaluated different unicast QoS delay-constrained least-cost (DCLC) routing algorithms according to four criteria: type of topology, size of a given topology in two dimensions, and delay constraint. They proposed an SDN-based four-dimensional evaluation framework in which they compared 26 DCLC algorithms. They concluded that in most of the 4D evaluation space, LARAC algorithm performs better than the other algorithms including Dijkstra algorithm in terms of delay optimization. Authors in Meng *et al.* (2014) used spatial reusability property of wireless network as a criterion to improve end-to-end throughput in wireless communication media. They proposed two algorithms SASR and SAAR based on linear programming for single path routing schemes. Another work based on OSPF Cianfrani *et al.* (2012) proposed a QoS-aware routing algorithm where a subnet of IP backbone routers is used to calculate the shortest path in terms of energy consumption of network elements.

An on-demand QoS routing protocol for mobile ad hoc networks (MANETs) with multi-class nodes is proposed in Du (2004). This protocol is based on TDMA technology to calculate the maximum available bandwidth and to reserve time slots for a given source-destination path. In this approach, there are two types of nodes, backbone nodes (B-nodes) with higher communication capabilities and general nodes with limited communication capabilities. The idea is to route traffic via B-nodes in order to meet the QoS requirements. A source node floods a route request to all intermediate B-nodes to reach the destination. Each intermediate B-node calculates the maximum available bandwidth up to its location and compares it with the requested bandwidth and based on this comparison, the B-node will either drop or forward the request. This solution considers a single QoS metric which is the bandwidth.

1.1.2.2 Multi-constrained routing solutions

A deadline-based resource allocation routing approach was proposed in Jagannath *et al.* (2016). The authors aimed to adapt routing protocols to different types of traffic as well as maximize the effective throughput of ad-hoc networks. They used the linear programming approach to solve the problem of maximizing utilities under the constraints of power, link capacity and Bit Error Rate (BER). Their solution has proven a high performance in terms of throughput and network reliability.Zhao *et al.* (2016) proposed a multi-constraint routing mechanism for smart grids communication. They used LARAC algorithm Juttner *et al.* (2001) to solve the dynamic routing problem. Their solution considers only delay and link throughput metrics in the shortest path problem.

1.1.3 Discussion

In general, most of existing routing solutions do not consider multi-metrics shortest paths which need to be determined in community network. In addition, their solutions compute the best path that minimizes flow cost between a single pair of nodes in the network. All-pair routing which is required in community network is not considered. Furthermore, neither the reliability of different wired-wireless accesses nor the overall network utilization cost is taken into account. These factors are very important in the context of community network.

1.2 QoS and QoE based scheduling solutions

Many scheduling algorithms have been proposed in previous work to manage different type of network traffic and provide ISP and/or user satisfaction based on different network or user parameters.

1.2.1 QoS based approaches

Yang *et al.* (2018) proposed a cloud-based scheduling solution to prioritize home applications based on packet inspection. The authors evaluate their solution using video streaming applications. Their architecture risks to let low-high priority queues starve since it considers only the static nature of priority assignments.

A number of approaches which considered some parameters besides QoS criteria to enhance network traffic scheduling are presented in Chaabnia & Meddeb (2018); Saidu *et al.* (2014); Sharma *et al.* (2018); Gueguen *et al.* (2013); Khoukhi *et al.* (2014). These approaches have considered the bandwidth criterion Chaabnia & Meddeb (2018); Khoukhi *et al.* (2014), the traffic load Saidu *et al.* (2014); Sharma *et al.* (2018) and the delay between source and destination nodes Khoukhi *et al.* (2014) as additional criteria to prioritize their traffic. Chaabnia & Meddeb (2018) contributed a new distributed model for home network traffic prioritization based on SDN technology. The authors implemented two-level slicing strategies; control-level slicing where traffic is prioritized based on bandwidth requirements and data plane level slicing where traffic is prioritized based on the type of application. Each data plane slice is associated with one control plane slice. The authors evaluate three scenarios of their solution; same priority slices, ascending order priority slices and descending order priority slices (referring to PQ). Packets with low priority in the second and third scenarios may suffer from the starvation problem.

Works in Saidu *et al.* (2014); Sharma *et al.* (2018) proposed dynamic scheduling algorithm using Weighted round-robin algorithm (WRR) a generated form of Fair Queuing (FQ), which allows, at each scheduling round, en/de-queuing a certain number of packets (weights) from each queue. Gueguen *et al.* (2013) proposed a cross-layer scheduler approach to extend wireless coverage by inciting potential network nodes to cooperate without deteriorating their QoS in terms of delay and throughput. A distributed traffic adaptation approach for wireless mesh networks (WMN) is proposed in Khoukhi *et al.* (2014) to control congestion and optimize network performance. This approach allows to regulate traffic by dropping best-effort traffic and adapting QoS-sensitive traffic rate based on two parameters; the delay between source and destination nodes and buffer occupancy of intermediate nodes. However, the slow network adaptation caused by the end-to-end based traffic regulation decision, make the system inappropriate for real-time applications.

Shakir & Rajesh (2017) contributed a two-level queuing model that considers the theoretical delay to provide QoS requirements in LTE networks. In the first layer queuing, packets are sorted based on their size, their expected departure time and the service time; then, they are scheduled to form calendar discs using a weighted fair queuing algorithm (WFQ). In the second layer queuing, the calendar discs are sorted based on their frequency bands and their corresponding packets are selected using Weighted round-robin algorithm (WRR), a generated form of Fair Queuing (FQ), which allows, at each scheduling round, en/de-queuing a certain number of packets (weights) from each queue. Abuteir *et al.* (2016) contributed a Wireless Network Assisted Video Streaming (WNAVS) framework which relies on SDN technology to schedule home packets based on real-time bandwidth allocation and network traffic statistics. However, their solution focuses only on one type of home application which is not the case for real home network traffic.

Recent scheduling approaches considered other scheduling criteria like the priority order of inserting packets Benacer *et al.* (2018) using a fixed priority algorithm based on Priority Queuing (PQ), user-defined profile priorities Bakhshi & Ghita (2016), user-defined context priorities (which includes the person's profiles, sensed data, e-Health services priorities and user preferences) Lemlouma *et al.* (2013), the currently active applications and devices Bozkurt & Benson (2016), the number of their direct neighboring nodes, the average link quality with these nodes, and the number of hops between the gateway and the smart community (SC) Bendouda *et al.* (2018) and the location of the congestion El Masri *et al.* (2014).

1.2.2 QoE based approaches

Anand & de Veciana (2017) contributed a multi-class scheduler which optimizes end-user QoE based on mean flow delay in wireless networks. Their solution uses a weighted Gittins index scheduler to optimize resources allocation for different classes of applications according to their sensitivity towards the mean delay. Hsieh & Hou (2018) proposed an online schedule which maximizes wireless network utility based on the QoE of each flow. The authors used the duration of video playback interruption to optimize QoE for video-on-demand applications under heavy-traffic conditions. Their solution proposed to schedule the client with the largest data rate in each scheduling period if there are no ties. If a tier occurs, the selected client is the one with the smallest product of its weight and the difference between the total amount of received data and the total number of bits that should have been played if there is no video interruption. Each client is assigned a weight by the access point that reflects its class of service. Zeng *et al.* (2018) contributed a scheduling scheme for Vehicle Ad-hoc Networks which increases the QoE of charging and discharging electric vehicles while optimizing the load capacity of the power grid. Each electric vehicle is matched to the charging station that maximizes its charging utility and has at least one free interface. Electric vehicles may cooperate in the same charging station by selling their electricities (discharging) to vehicles with low battery levels. The cooperative electric vehicles charging and discharging is scheduled using a Pareto Optimal Matching Algorithm.

1.2.3 QoS and QoE based approaches

Bakhshi & Ghita (2016) proposed a queuing model that considers user-defined profile priorities to optimize bandwidth allocation in-home network. Their solution is based on Software Defined Network (SDN) technology to calculate user-profiles in a central controller which resides on the cloud and push the resulting rules on home gateway. The authors evaluate their solution using multimedia and video streaming applications. Their solution has shown a good performance in terms of latency and packet loss for only a selected set of high priority users. Butt *et al.* (2018) proposed a cross-layer scheduling framework over fading channels which guarantees the minimum QoS requirements in terms of energy consumption while satisfying the QoE in terms of loss tolerance for loss-tolerant applications in the 5G wireless network. The authors used the Markov decision process to model their scheduling problem, and they used stochastic optimization techniques to solve it.

Zheng *et al.* (2017) proposed a task layer scheduling scheme to improve QoE in terms of the quality of the transmission of a group of packets (called task) rather than the quality of the link in wireless networks. Each link can support many tasks from different class of services with different delay constraints. Their solution calculates the remaining time of each task and each link. Then, the link with the least remaining time is selected to schedule tasks with the fewest packets. Authors considered the QoE using the global throughput and the QoS using maximum delay for each class of service. Fan & Zhao (2018) contributed a cross-layer scheduling scheme for video streaming which considers the average end-to-end delay and the frame buffer level at the destination nodes to improve both QoS and QoE in wireless Ad-hoc networks. The authors used the Lyapunov optimization framework to solve the optimization problem and proposed a distributed media access control algorithm to reduce computational complexity.

1.2.4 Discussion

In general, most of the existing scheduling solutions rely on static metrics in the priority assignment task. They are either based on user-defined profiles, current active applications or class of service. Even though there are solutions that assign priorities dynamically (based on real-time bandwidth allocation or source-destination distance), they consider a specific type of home application (multimedia and video streaming applications) or only a particular optimization goal. They either focus on improving QoS from the perspective of ISP (optimize bandwidth utilization based on traffic loads to meet ToS priorities) or improving QoE from the perspective of the home user (optimize delay based on the distance between the source and destination nodes). Table 1.1 summarizes the existing QoS and QoE based solutions.

Specific queuing metrics, which need to be determined in smart home network, like traffic application criticality (or type of service) and the maximum required delay along with heterogeneous distributions queuing adaptability, has never been taken into account. These factors are very important in the context of the home network to fill the gap between QoS and QoE for any home application in an automated way.

Table 1.1 QoS and QoE based solutions.

ref	QoS	QoE	Method	Applications/Scope
Butt *et al.* (2018)	Energy	Loss	Markov decision process, stochastic optimization technology	Loss tolerant applications in 5G
Bakhshi & Ghita (2016)	Bandwidth	User-defined profiles	SDN	Multimedia and video streaming applications
Abuteir *et al.* (2016)	Bandwidth	Network traffic statistics	SDN	Video streaming
Fan & Zhao (2018)	Bandwidth	Frame buffer level at destination node	Lyapunov optimization framework	Video streaming
Shakir & Rajesh (2017)	Delay	Frequency bands	WFQ, WRR	LTE networks

1.3 Concurrent traffic scheduling

Various scheduling strategies have been deployed in smart home context to improve energy efficiency Zhou *et al.* (2016); Chen *et al.* (2013), reduce power consumption Khan *et al.* (2019) and improve response time Leu *et al.* (2014). However, the multi-channel/port concurrency issue has not yet been considered in the smart home network.

The problem of providing concurrent accesses to a shared resource has been considered in several research areas; telecommunications Ding *et al.* (2018); Wang *et al.* (2018); Ma *et al.* (2019); Misra & Sarkar (2015); Wang *et al.* (2018); Jiang *et al.* (2019); Zhang *et al.* (2017), vehicular networks Zhang *et al.* (2019), computer systems Kim *et al.* (2019); Wang *et al.* (2019), etc.

Zhang *et al.* (2019) proposed a broadcast protocol for vehicular ad-hoc networks (VANETs) which enables candidate forwarders in different transmission segments to concurrently transmit message packets. The authors used an accurate time synchronization mechanism to precisely calculate the packet forwarding time for each transmitter to satisfy concurrent transmissions requirements of orthogonal frequency division multiplexing (OFDM) signals in terms of the maximum temporal displacement. Despite the good performance provided by this solution in terms of the total broadcast delay, the large number of the concurrently transmitted messages can cause packet loss.

Many efforts have been done to improve spatial multitasking either through adding additional resources like multiple CPU cores or by maximizing thread-level parallelism Kim *et al.* (2019). Ding *et al.* (2018) contributed a new concurrent scheduling algorithm for wireless backhaul networks using contention graph. The spatial reuse of multiple flows is provided by the full-duplex aspect given the self-interference cancelation technology in mmWave networks besides its huge bandwidth. A new protocol for wireless sensor networks (WSN) is proposed in Ma *et al.* (2019) to enable concurrent transmission under interference. The protocol uses channel hopping to maintain communication with a continuous transmission when interference occurs. In Wang *et al.* (2018) a routing design for concurrent transmission is proposed. This design is based on the concurrent decomposition modular in the physical layer used by the collision avoidance techniques.

1.3.1 Game theory scheduling

Game theory has been used in different research areas Misra & Sarkar (2015); Asadi & Mancuso (2017); Wang *et al.* (2018); Jiang *et al.* (2019); Wang *et al.* (2013). An evolutionary game-theoretic approach is considered in Misra & Sarkar (2015) to reduce the average waiting time for local data processing units (LDPUs) in wireless body area network (WBAN). This approach uses the hawk-dove game to prioritize LDPUs based on the dissipated energy, the number of time slots the LDPU has been idle and the age and the gender of a person. A non-cooperative stochastic game is considered in Wang *et al.* (2018) to bypass malicious nodes in cognitive radio networks. Since a normal/malicious unlicensed user attempts to maximize/minimize the expected average of the cumulative link utility along its selected path (defined as the ratio of the link distance by the expected link delay), the authors calculated a Nash equilibrium to select the channel which maximizes this utility. A coalition game-theoretic approach is used in Asadi & Mancuso (2017) to solve the cluster formation problem in Device-to-Device (D2D) communications in 5G cellular networks. The game is used by the LTE base station to let the user join or leave a cluster based on its energy efficiency. Another coalition game is considered in Jiang *et al.* (2019) to enable full-duplex concurrent scheduling in millimeter wave wireless backhaul network. The game is used to find concurrently scheduled flows set with the maximum sum rate which maximizes the number of flows which satisfy their QoS requirements.

1.3.2 Discussion

In general, prior work focus on parallel executions that require high-performance computing Zhang *et al.* (2019); Wang *et al.* (2019) and advanced hardware or protocol designs Wang *et al.* (2018); Ma *et al.* (2019) that require significant hardware or protocol modifications. However, a home gateway is a limited-resource system with limited bandwidth and computational capabilities compared to 5G and WSN networks Ding *et al.* (2018). This makes it difficult to deploy such complex, time and space-consuming approaches on a smart home gateway. Also, multiple access solutions provided by multiplexing systems Han *et al.* (2016) enable simultaneous transmissions over only a single communication channel. Multi-Channel Concurrency (CCM) Anand *et al.* (2015) in wireless systems allows concurrent multiple access over different channels from a single radio interface through using static or dynamic schedulers to control the switching frequency and the time allocation for each channel. These implementations cannot handle multi-channel/port concurrency issue.

1.4 General discussion

Optimizing routing task has always been a key feature to improve network communication. However, prior works are no longer appropriate for the future smart home networks requirements. With a target to reduce latency and the use of network resources between all pairs of nodes in a heterogeneous wired-wired network, traditional routing protocols focused on the choice of the most optimized one-pair-node shortest path without considering the particular architecture of the smart home networks, which is very dense, dynamic and heterogeneous.

On the other hand, traffic scheduling systems have been evolved to handle different types of applications. However, theses solutions are no longer efficient in future smart home network since they consider only a particular optimization goal and they use Type of Service (ToS) field to assign priorities in order to either improve QoS from the perspective of the Internet service provider (ISP), or improve QoE from the perspective of the end user. Also, prior works on traffic concurrency consider only concurrent traffic from the same media access (from the same network channel or port). There is no appropriate queuing model that cover both QoS and QoE requirements and fairly schedule concurrent traffic over different network channel/ports. These requirements are very important for smart home network and should be addressed to avoid potential damage in a critical dynamic multi-sourced network traffic.

CHAPTER 2

OBJECTIVES AND GENERAL METHODOLOGY

2.1 Positioning of our Research project

Optimizing routing task has always been a key feature to improve network communication. However, prior work are no longer appropriate for the future smart home networks requirements. With a target to reduce latency and the use of network resources between all pairs of nodes in an heterogeneous wired-wired network, traditional routing protocols focused on the choice of the most optimized one-pair-node shortest path without considering the particular architecture of the smart community network, which is very dense, dynamic and heterogeneous.

On the other hand, traffic scheduling mechanisms have been evolved to handle different types of applications. However, these solutions are no longer efficient in future smart home network since they consider only a particular optimization goal and they use Type of Service (ToS) field to assign priorities in order to either improve QoS from the perspective of the Internet service provider (ISP), or improve QoE from the perspective of the end user. Also, prior works on traffic concurrency consider only concurrent traffic from the same media access (from the same network channel or port). There is no appropriate queuing model that cover both QoS and QoE requirements and fairly schedule concurrent traffic over different network channel/ports. These requirements are very important for smart home network and should be addressed to avoid potential damage in a critical dynamic multi-source network traffic.

2.2 Research hypothesis

The research hypothesis (RH) of this thesis is defined as follows:
RH: By optimizing routing with QoS in inter-SHNs and traffic processing in intra-SH gateway and by controlling resource sharing for concurrent traffic over different media accesses, we improve network performance, enhance traffic concurrency and minimize the cost of future smart home networks.

2.3 Objectives

2.3.1 Main objective

The main objective (MO) of this thesis is defined as follows:
MO: Design an efficient network control mechanism for future smart home architectures that minimizes delay, packet loss, bandwidth and caching overhead for paths between all wired-wireless pairs of nodes in inter-SHNs and controls queuing for smart home traffic in an optimal way to efficiency meet their QoS and QoE requirements, fairly schedule concurrent flows from different media accesses and reduce the total scheduling delay.

2.3.2 Specific objectives

2.3.2.1 Specific objective SO1

SO-1: Optimize routing with QoS in inter-SHNs: This includes minimizing path costs by QoS.
In order to minimize path cost by QoS in inter-SHNs, we need to determine minimal costs between all wired-wireless pairs of nodes in terms of delay, packet loss, bandwidth consumption and access point caching overhead. Thus our objective is to create an efficient multi-constrained all pair QoS-aware routing approach in inter-SHNs.

2.3.2.2 Specific objective SO2

SO-2: Optimize traffic queuing with QoS and QoE in smart home network.
In order to deploy an optimized scheduling scheme specific to the smart home network context, we need to consider the mixed arrival distributions of home traffic, the critical nature of the application and the maximum allowed delay. Thus our objective is to build an efficient QoS and QoE-aware scheduling approach for smart home multi-sourced traffic.

2.3.2.3 Specific objective SO3

SO-3: Optimize scheduling of concurrent traffics in smart home network: This includes concurrent traffics from different communication channels/ports and with the same QoS level.
In order to optimize traffic concurrency scheduling in smart home network, we need to fairly share home gateway resources in order for each concurrent traffic to meet its QoS requirement in terms of delay. Thus our objective is to design and implement an optimized QoS-aware and fair scheduling approach for smart home concurrent traffic over different communication channels/ports.

2.4 General methodology

We propose three methodologies M1, M2 and M3 to respectively address the research questions RQ1, RQ2 and RQ3 as well as the specific objective SO1, SO2 and SO3. The three methodologies are defined as follows:

2.4.1 Methodology M1

The methodology M1 addresses the research question RQ1 and the specific objective SO1. In this methodology, we present a QoS-Aware Software-Defined Routing (QASDN) algorithm that uses Software-defined networking (SDN) technology and determines the minimal cost between all pairs of nodes in the network taking into account the different types of physical accesses and the network utilization patterns. The methodology M1 is summarized as follows:

- Provide a routing solution for heterogeneous wired-wireless inter-SHNs.
- Improve traditional Lagrangian Relaxation Based Aggregated Cost (LARAC) algorithm to determine the minimal costs of flows among all pairs of nodes in a community network.
- Add network utilization cost in terms of bandwidth consumed by the APs to the QoS routing problem, taking into account the reliability (in terms of packet loss) of different types of physical accesses.

- Assigns optimal APs (or ARs) to cache data on the optimal path.

2.4.2 Methodology M2

The methodology M2 addresses the research question RQ2 and the specific objective SO2. In this methodology, we present a new queuing model (QP-SH) for QoS-level Pair traffic with mixed arrival distributions in Smart Home network to make dynamic QoS-aware scheduling decisions meeting delay requirements of all traffic while preserving their degrees of criticality. The methodology M1 is summarized as follows:

- Propose a new queuing metric combining the ToS field and the maximum number of packets that can be processed by the system's service during the maximum required delay.
- Build a new scheduling model for multi-sourced traffic generated with different distributions.
- Optimize the number of packets that meet their allowed delay while preserving their degree of criticality.

2.4.3 Methodology M3

The methodology M3 addresses the research question RQ3 and the specific objective SO3. In this methodology, we present a new queuing model (QC-SH) for concurrent traffic in Smart Home network. The methodology M1 is summarized as follows:

- Propose an analytic model for optimizing concurrent packet scheduling in a smart home network with mixed arrival distributions and different QoS requirements.
- Introduce an innovative probabilistic queuing model in a smart home network which provides a fair scheduling between concurrent traffic belonging to different media access.
- Define a bidding game to model concurrent traffic scheduling in smart home network that reduces the total processing delay.

- Propose a free-overhead implementation model on both sides; traffic sources and the home gateway.

2.4.4 Application of the Methodology to the Case Study

We applied the methodology discussed in this thesis to the Smart ÉTS Residence in Montreal (Canada), under the "Star ÉTS: A Sustainable Cloud-Based Smart ÉTS Residence" project Nguyen & Cheriet (2016) as shown in Fig.2.1. The smart residence testbed covers about 150 rooms, 150 WiFi access points (APs) in public space and servers more than 300 students.

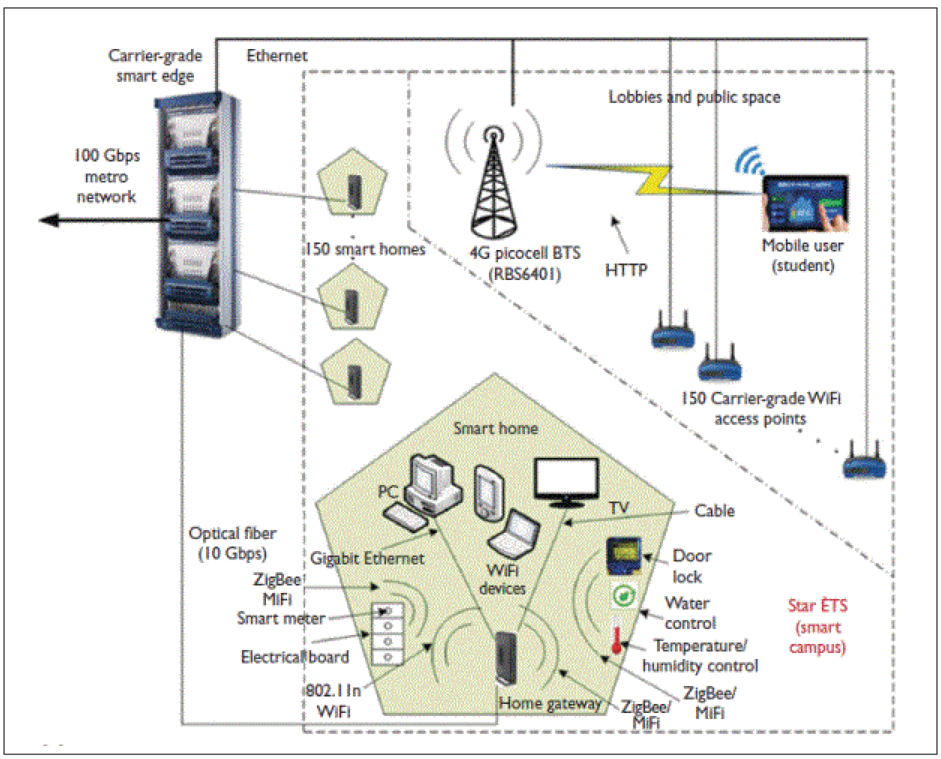


Figure 2.1 The Smart Residence testbed Nguyen & Cheriet (2016).

Each home has a gateway connected to a core switching platform integrated into the smart edge that presents an exit point to the external network, links the community to an Internet service provider (ISP) through an Ethernet cable or optical fiber and, provides SDN functions. Home gateways are connected to the APs through WiFi technology and the small distance between two homes makes a home access point capable of serving more than one home at a time. Thus, the proposed QASDN algorithm applied to the access points and home gateways provides the minimal cost between all pairs of nodes in the heterogeneous wired-wireless inter-SHNs taking into account the network utilization patterns.

In addition, home gateways offer services to a wide range of application like monitoring, health assistance, safety and energy efficiency, which require diverse resources in terms of bandwidth, delay and memory, producing traffics with different Quality of Service (QoS) levels. Thus, the proposed QP-SH algorithm applied to home gateways, provide dynamic QoS-aware scheduling between multi-sourced traffic generated with different distributions taking into account their delay requirements and their degrees of criticality. Furthermore, the QC-SH algorithm provides fair scheduling between concurrent Intra-SHN traffic belonging to different media access.

We defined a central controller located in the smart edge to control the access points and home gateways and applying the proposed scheduling and routing methods.

A summary Diagram of the thesis is presented in Fig.2.2.

2.5 Experimental Environment

In this thesis, we propose a scalable routing architecture for a smart home topology with 150 network nodes. In order to provide routing and scheduling solutions for heterogeneous wired-wireless inter-SHNs, we propose a network virtualization framework based on SDN technology and uses OpenFlow enabled routers. We started by compiling and executing the controller "OpenDaylight" (Helium distribution) under the following configuration:

- Java 7 JDK
- Maven v 3.3.2 (for the compilation)
- OVSDB (Open vSwitch Database)
- DLUX (DayLight User eXperience)

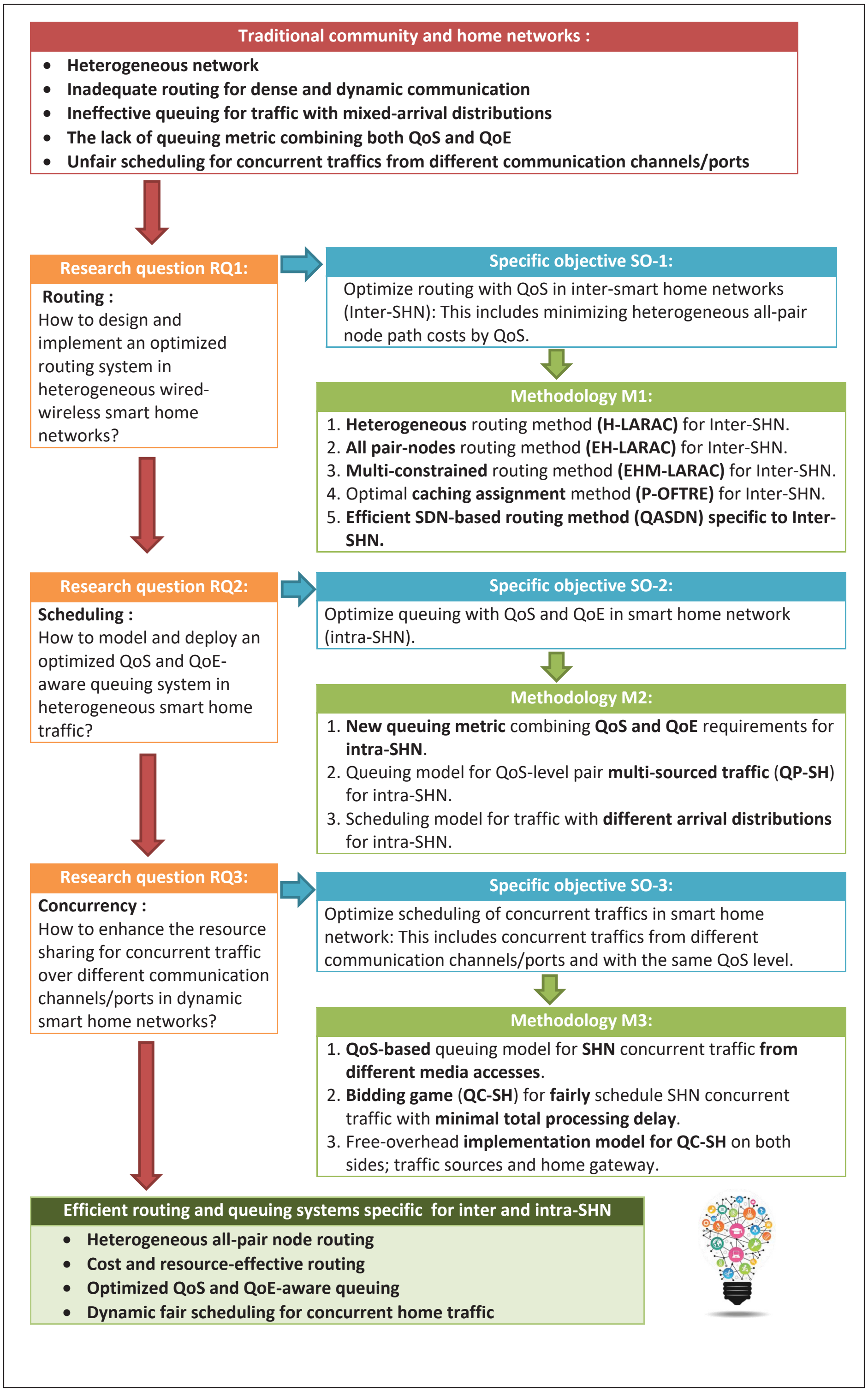


Figure 2.2 Diagram of the thesis.

A simulation environment was set up with the "Mininet" simulator. With this simulator, various network topologies were tested and the simulated network flow was checked through the installation of certain routing rules with OpenFlow (Appendix I.1). Then the communication between the virtual home gateway and the outside world was established (Appendix I.2).

Then, the topology was tested with a real router (initially based on the DDWRT system) under the following configuration:

- "OpenWrt" operating system that supports OpenFlow
- "openvswitch: OVS" software (Appendix II.1). OVS is a multilayered virtual switch (freely licensed) designed to enable massive network automation (through programmatic expansion) while supporting standard management interfaces and protocols and to support distribution on multiple physical servers.

Afterward, the deployment done in the virtual environment was applied to a real router(Buffalo wzr1750) in order to establish a connection to an external device (Appendix II.2).

CHAPTER 3

QOS-AWARE SOFTWARE-DEFINED ROUTING IN SMART COMMUNITY NETWORK

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3.1 Abstract

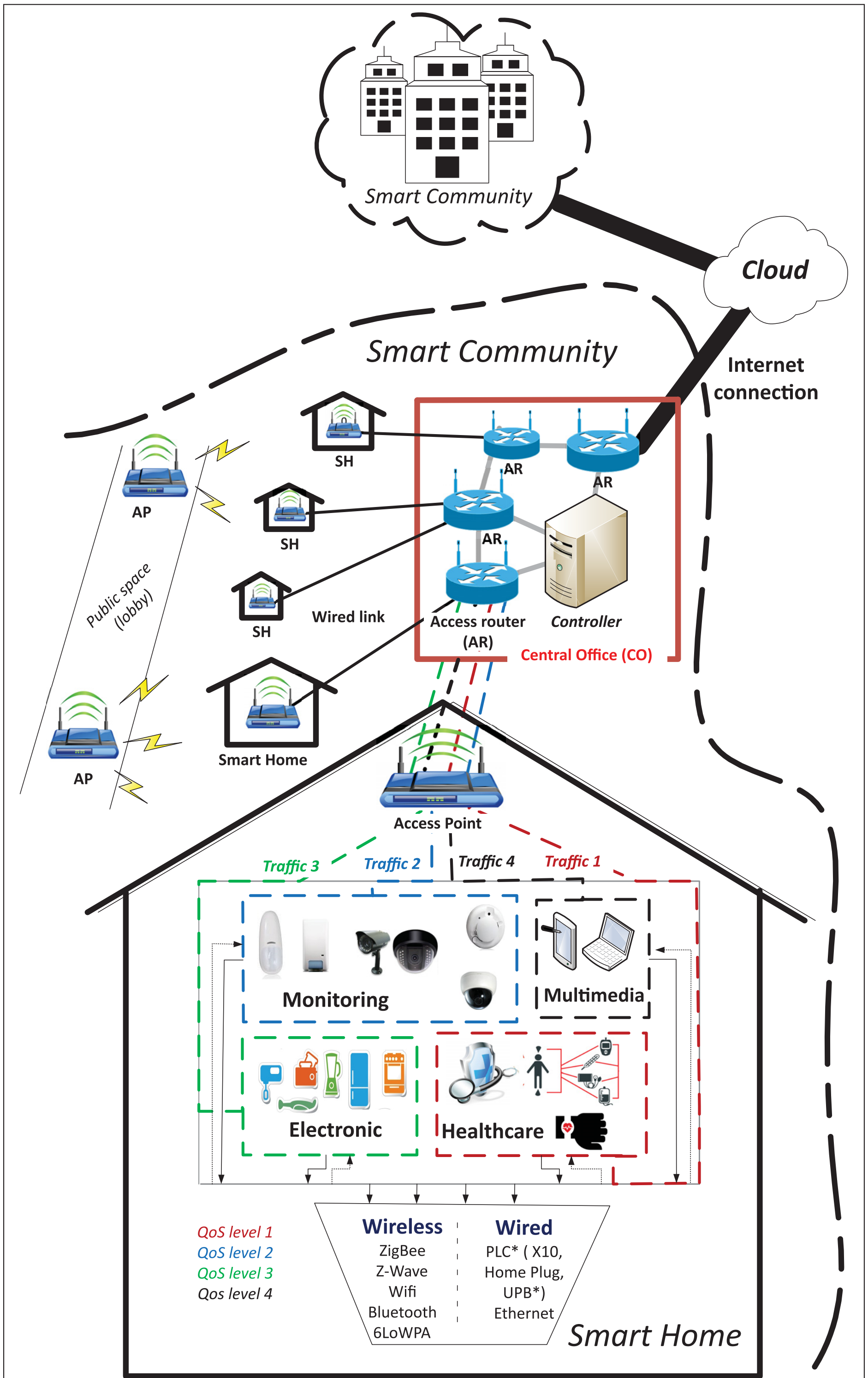
Community networks are evolving rapidly to include heterogeneous physical access (both wired and wireless) and a large number of smart devices that generate different types of traffic. In addition, a variety of applications (VoIP, messaging, video, etc.) with different requirements is putting more constraints in community networks such as delay, packet loss, and bandwidth. Due to its particular architecture, which is very dense and very dynamic, the traditional one-pair-node shortest path solution, which is currently used in metro or WAN networks, is no longer efficient in community networks. This paper presents an analytical framework for dynamically optimizing data flows in community network using Software-defined networking (SDN). We formulate a QoS-based routing optimization problem as a constrained shortest path problem, and then propose an optimized solution to determine minimal cost between all pairs of nodes in the network taking into account the different types of physical accesses and the network utilization patterns. Our experiments show the proposed solution improves resource utilization up to 90%, and outperforms the traditional shortest cost based algorithm with a gain that reaches 13% for the majority of criteria, with 83% for distance, 77% for bandwidth and 51% for packet loss.

Keywords: Smart community, dynamic quality of services, route optimization, OpenFlow network

3.2 Introduction

Community network is an IP-based network that creates “a wireless mesh network among citizens, providing a network that is independent, free, and (in some cases) available where regular Internet access is not”Hardes *et al.* (2017). Smart home is an attractive practice of smart community network which is “a multihop network of smart homes that are interconnected through radio frequency following wireless communication standards such as WiFi (IEEE 802.11)” Li *et al.* (2011) as well as wired communication standards. In a community network, all paths between source-destination pair of nodes need to be determined in order to reduce the communication cost of last-mile applications and improve interaction among users in a smart community. For example, if an end user wants to share his TV screen with others within a smart community to broadcast news, the shortest paths from his home to all other nodes in the community has to be determined. Another example is public safety: if an illegal penetration is detected in a home, all neighbors must be notified immediately to apply appropriate protections. This requires communication among all pair of nodes to be established dynamically with a highest priority. The high level of cooperation within smart homes imposes new challenges on community network management and traffic engineering. Traditional single path end-to-end routing protocols become no longer appropriate.

Fig.3.1 depicts a typical smart community network. Each home has an access point (AP) connected to an access router located in a central office (CO) through an Ethernet cable or optical fiber. An egress router links the community to an Internet service provider (ISP). There are also several APs in public space. All APs can be mesh-connected. Such a network offers services to a wide range of application like monitoring, health assistance, safety and energy efficiency, which require diverse resources in terms of bandwidth, delay and memory, producing traffics with different Quality of Service (QoS) levels Simon & Kavitha (2017b); Ingle & Gawali (2011); Gomez & Paradells (2010)(marked by different colors in Fig.3.1). Moreover, a large



*PLC (Power Line Communications)

*UPB (Universal Powerline Bus)

Figure 3.1 Smart community network.

number of devices in the community generate a huge volume of data which deteriorates home network QoS in terms of latency and packet loss. Best-effort services that do not provide information about whether data is delivered or not and do not guarantee any QoS, are arbitrarily delayed, corrupted or duplicated and can even be lost. This may have significant impacts on delay-sensitive applications like VoIP (it causes an unacceptable delay in the conversation) and online games (it will make the game unplayable). Thus, the most challenging issue faced by community network is to provide Quality of Experience (QoE) especially to delay-sensitive applications that require QoS Jarschel *et al.* (2011, 2013); Li *et al.* (2016b); Premarathne *et al.* (2017b). In addition, community network topology has a very high density of nodes communicating simultaneously with each other. In such network, we need to calculate paths between all source-destination pairs of nodes within a minimum of time and space computational overhead. Along with the increasing size of the community network, this makes traditional routing approach, which is used on the Internet, no longer efficient in terms of resource allocation and operational costs. Software-defined network (SDN) technology Hu *et al.* (2014) brings new solutions to simplify and optimize network man-agement by moving all complex computational tasks (including QoS analysis and decisions) from hardware network devices to a centralized control Tootoonchian *et al.* (2012) which may reside on the cloud. Thus, network device becomes a simple data collector and behavior executor. SDN can significantly improve community network management by affording a view of how users network is used while providing a single point of control.

The deployment of a smart community architecture based on SDN allows users to seamlessly move across various wired and wireless infrastructures which can be managed by different vendors.

Furthermore, the "software-defined" feature of the SDN technology allows reconfiguration by enabling administrators to easily collect signals or modify parameters in the packets and to quickly compute a suitable path. This ultimately leads to a self-adaptive environment that is capable of dealing with both wired and wireless devices from different types. However, smart community raises some challenges related to performance and resource management

Karakus & Durresi (2017); Han *et al.* (2016); Hassan *et al.* (2017); Rademacher *et al.* (2017). For example, if an AP within a smart community wants to send the same data to multiple destination nodes, it has to find the shortest paths from its location to each destination, then it will forward the full sized data directly to each destination all along its shortest path. Sending multiple copies of full sized data will increase the bandwidth utilization cost. This problem can be solved by caching data into an AP (or AR) within the shortest path between source and destination nodes. This AP (or AR) will send encoded data rather than full sized data and then reduce bandwidth consumption. The huge volume of data generated by numerous devices in the community resulting in huge number of cached data in APs will saturate the memory of AP. Therefore, memory size in each AP faces scalability concerns in a dense network environment. Thus, in order to reduce AP memory consumption, AP memory management like caching need to be optimized.

3.2.1 Contribution and Structure of this Paper

Most of the previous work that target routing problems Cui *et al.* (2013); Egilmez *et al.* (2013) cannot be efficiently applied in a community network since they do not consider key factors such multi-metrics shortest path, all-pair routing, the reliability of different types of physical accesses and the overall network cost Fuchs (2017). In this paper, we propose an analytical framework for dynamically optimizing data flows in community networks using SDN. The contributions of this paper include:

- A formulation of the multi-constrained all-pair QoS-aware routing problem in smart community network.
- An algorithmic solution to both multi-constrained all-pair routing and QoS-based caching problems.

To the best of our knowledge, this is the first software defined multi-constrained all-pair QoS-based routing and caching solution in smart community network and our algorithms outperform prior work in overall when taking into account the different QoS constraints. In this work we pose an unsplittable routing problem in which each source-destination pair of nodes must have only one shortest path.

The rest of the paper is organized as follows. We discuss related work on QoS based routing in Section 3.3 In Section 3.4, we present a model of the community network with QoS constraints. QoS based routing problem and Problem formulation are introduced in Sections 3.5 and 3.6. A Lagrangian Relaxation Based Aggregated Cost (LARAC) algorithm for QoS enabling multi-constrained routing is described in Sections 3.7 and 3.8. Performance results of our solution are provided in Section 3.9. Finally, we draw conclusions and present future work.

3.3 Related work

Different routing protocols have been proposed according to the application or the network architecture. A deadline-based resource allocation routing approach was proposed in Jagannath *et al.* (2016). The authors aimed to adapt routing protocols to different types of traffic as well as maximize the effective throughput of ad-hoc networks. They used the linear programming approach to solve the problem of maximizing utilities under the constraints of power, link capacity and Bit Error Rate (BER). Their solution has proven a high performance in terms of throughput and net-work reliability. Huang *et al.* (2016) used graph theory to solve the throughput maximization problem in SDN. They proposed two algorithms: one for snapshot scenario where requests arrive on the same time, and the other for online scenario where requests arrive one by one. Their solution has shown a good performance for both algorithms in terms of the number of requests, the runtime and the quality of solutions delivered.

Authors in Amokrane *et al.* (2015) solved the high-energy consumption problem in campus networks, which is formulated as an Integer Linear Program (ILP). They proposed an online per flow routing algorithm (AC-OFER), in SDN, based on ant colony approach. This algorithm allows dynamic reconfiguration of flow routing and device status by switching off/on network devices and taking into account bandwidth and delay constraints. Their solution reduces more energy consumption than the shortest path routing. Han *et al.* (2016) contributed a QoS-aware routing framework for Wireless Multimedia Sensor Networks (WMSN) in SDN. Their solution, which is based on Open Shortest Path First (OSPF), computes the suitable path meeting QoS requirements for delay-sensitive flows, bandwidth-sensitive flows and best-effort flows. Another work based on OSPF Cianfrani *et al.* (2012) proposed a QoS-aware routing algorithm where a subnet of IP backbone routers is used to calculate the shortest path in terms of energy consumption of network elements.

Lin *et al.* (2017) introduced a QoS-aware routing architecture for SDN switches and legacy switches, which includes an Simulated Annealing based QoS-aware Routing (SAQR) algorithm that uses the Spanning Tree protocol as network discovery mechanism. The proposed SAQR algorithm provides an adaptive tuning for delay variation, loss rate and bandwidth deviation. Authors in Meng *et al.* (2014) used spatial reusability property of wireless network as a criterion to improve end-to-end throughput in wireless communication media. They proposed two algorithms SASR and SAAR based on linear programming for single path routing schemes. Zhao *et al.* (2016) proposed a multi-constraint routing mechanism for smart grids communication. They used LARAC algorithm Juttner *et al.* (2001) to solve the dynamic routing problem. Their solution considers only delay and link throughput metrics in the shortest path problem.

Egilmez *et al.* (2013) contributed a new QoS architecture based on OpenFlow protocol as well as a priority based dynamic routing optimization framework. Their framework aims at optimizing routing decisions in order to provide QoS (in terms of packet loss and delay variation). The authors apply their framework on QoS-based routing of a video stream with three QoS levels: QoS Level 1 contains dynamically transmitted flows with the highest priority, QoS Level 2 contains dynamically transmitted flow after fixing routes of Level 1, and finally Best-effort contains the flows transmitted by the shortest path (not dynamic). The authors presented the dynamic routing with QoS as a constraint to the shortest path problem. Their solution, based on LARAC optimization, computes the best route that minimizes the cost function (delay variation and packet loss) while keeping delay variation lower or equal to a specified value. The authors showed their framework meets the service level requirements of broadcast video in most cases. Guck *et al.* (2017) evaluated different unicast QoS delay-constrained least-cost (DCLC) routing algorithms according to four criteria: type of topology, size of a given topology in two dimensions, and delay constraint. They proposed a SDN-based four-dimensional evaluation framework in which they compared 26 DCLC algorithms. They concluded that in most of the 4D evaluation space, LARAC algorithm performs better than the other algorithms including Dijkstra algorithm in terms of delay optimization.

In addition, most existing hierarchical routing protocol (heterogeneous/homogeneous wireless/wired sensor network routing approaches) mainly focus on reducing energy and increasing network lifetime rather than QoS support like QoS-based routing protocols. Du & Lin (2005) proposed a routing protocol (HSR) for Heterogeneous sensor networks (HSN). The network is composed of a large number of low power nodes and small number of high power nodes. Each low power node sends data to the neighbor that has the shortest distance to the high power node using a greedy routing protocol. Each high power node sends data to the neighbor high power node. In this approach, both types of nodes are static and are uniformly and randomly distributed in the network. The solution shows a good performance in terms of throughput and energy savings, however, it is only based on a single metric (distance) shortest path algorithm; it doesn't consider the capability of each node QoS routing, and the static network topology is not suitable for many applications.

Du *et al.* (2009) contributed a routing protocol for key management based on Elliptic Curve Cryptography (ECC) public key algorithm to enforce security, reduce energy consumption and improve storage requirement for key sharing among low power nodes in HSN. The authors proposed a centralized and distributed approaches for their ECC-based key management scheme. In the centralized approach, each high power node broadcasts the routing structure information to its low power nodes using their public keys and verifies newly-deployed nodes using a special key. In the distributed approach, each high power node generates and signs a certificate to its low power nodes using their MAC and public keys. In this approach, each low power node stores a pair of ECC keys as well as public keys of its high power node. In both approaches, nodes are deployed according to a predefined topological tree structure, however, in the case of an undefined network topology, each low power node will stores the public keys of all high power nodes (since it doesn't know its corresponding high power node), this will rise storage and energy issues in low powered nodes as well as security issues.

Another hierarchical structure routing protocol (ERP) is proposed by Bara'a & Khalil (2012). It is aimed to find the optimal number of cluster heads and their locations in a heterogeneous wireless sensor network (HWSN) in order to reduce energy consumption and prolongs the network lifetime (by minimizing the total number of cluster heads) as well as the stability period (by decreasing transmission distance). To this end, they introduced cluster's cohesion metric (which is the sum of the smallest distances between a non-cluster head node and its cluster head node, for all cluster heads in the system), and cluster separation metric (which is the minimum Euclidean distance between any pair of cluster heads in the system). Although this approach improves network lifetime and stability period, it uses an iterative optimization scheme for the selection of the best breed for cluster heads that makes an extra delay and overhead in the setup phase of each network transmission round.

An on-demand QoS routing protocol for mobile ad hoc networks (MANETs) with multi-class nodes is proposed in Du (2004). This protocol is based on Time Division Multiple Access technology (TDMA) to calculate the maximum available bandwidth and to reserve time slots for a given source-destination path. In this approach, there are two types of nodes, backbone nodes (B-nodes) with higher communication capabilities and general nodes with limited communication capabilities. The idea is to route traffic via B-nodes in order to meet the QoS requirements. A source node floods a route request to all intermediate B-nodes to reach the destination. Each intermediate B-node calculates the maximum available bandwidth up to its location and compares it with the requested bandwidth and based on this comparison, the B-node will either drop or forward the request. This solution considers a single QoS metric which is the bandwidth.

In general, most of existing routing solutions rely on either link quality metrics or wireless spatial reusability metrics to compute the best path that improve a single type metric-based cost function. Multi-metrics shortest paths which need to be determined in community network, has never been taken into account. In addition, their solutions are limited in minimal costs of flows between a single pair of nodes in the network. All-pair routing which is required in community network is not considered. Furthermore, neither the reliability of different types of physical accesses nor the overall network utilization cost is taken into account. These factors are very important in the context of community network.

Our approach mitigates these limitations through designing novel algorithmic solution that consider important key factors such all-pair routing, multi-constrained QoS-based routing, the reliability of different types of physical accesses, and QoS-based caching solutions in order to adapt the traditional constraint-based shortest path approach to the smart community network context. More specifically we propose a QoS-Aware Software-Defined Routing (QASDN) algorithm that:

(a) Provides the solution for routing in heterogeneous wired-wireless smart community network,
(b) Optimally improves the LARAC algorithm to determine the minimal costs of flows among all pairs of nodes in a community network,
(c) Adds network utilization cost in terms of bandwidth consumed by the APs to the QoS routing problem, taking into account the reliability (in terms of packet loss) of different types of physical accesses,
(d) Assigns optimal APs (or ARs) to cache data on the optimal path.

To that end, we gradually add new criteria to the traditional LARAC algorithm, namely: heterogeneous routing, all-pair routing, network utilization cost, reliability of wired-wireless accesses and caching. This results in four new models and algorithms: i) H-LARAC which is obtained by adding the heterogeneity of physical accesses to the traditional LARAC algorithm (Section 6.1), ii) EH-LARAC algorithm, by adding all-pair routing to H-LARAC (Section 6.2), iii) EHM-LARAC algorithm, by adding network utilization cost and reliability of heterogeneous physical link to EH-LARAC algorithm (Section 6.3), and iv) P-OFTRE algorithm, which is designed to optimize the cache assignment on optimal paths obtained by EHM-LARAC (Section 7).

3.4 System Model

Smart community network is a heterogeneous infrastructure made of multiple physical accesses like wired and wireless. Low-power wireless mesh networks are often used in smart grid and smart city applications. These networks are based usually on a routing sub-layer between layer 2 (link) and layer 3 (network) of OSI model.

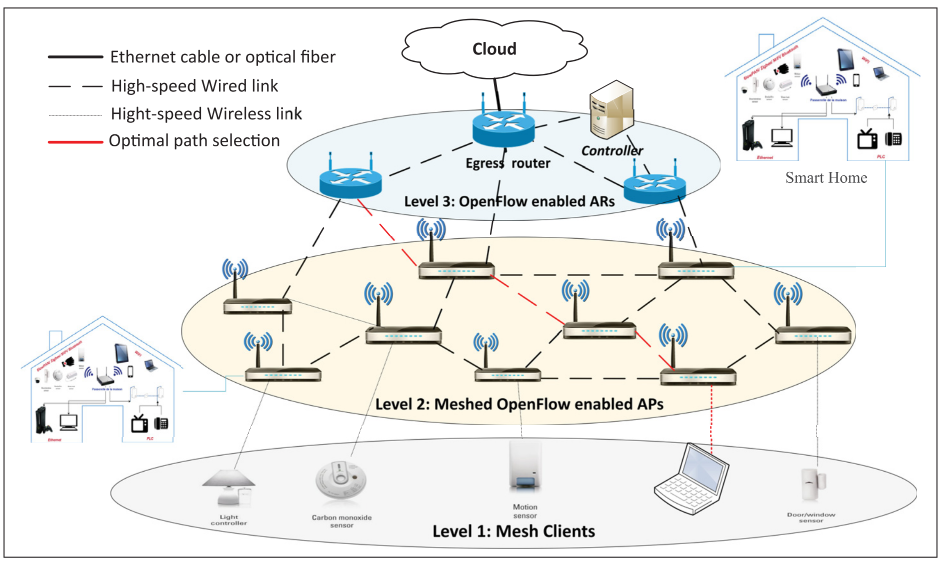


Figure 3.2 Software-defined smart community network.

Fig.3.2 illustrates an example of the smart community network using a SDN controller and OpenFlow enabled ARs and APs. Each home has an AP (at mesh layer 2) that is connected to a communit's access router (at mesh layer3) as an exit point to the external network using a high-speed wired link. The small distance between two houses makes a domestic AP capable of serving more than one house at a time. The communication among APs can be done through a wired or a wireless link. At mesh layer 1, user terminals are connected to the Meshed APs wirelessly using the highest Received Signal Strength (RSS). However, the selection of the suitable path is based on the end-to-end cost of end-to-end link that can be calculated by the

SDN controller. In our proposed architecture (Fig.3.1), the controller is running on a commodity server on the CO (the CO may be virtualized). Therefore, the delay between the controller and the switch is negligible.

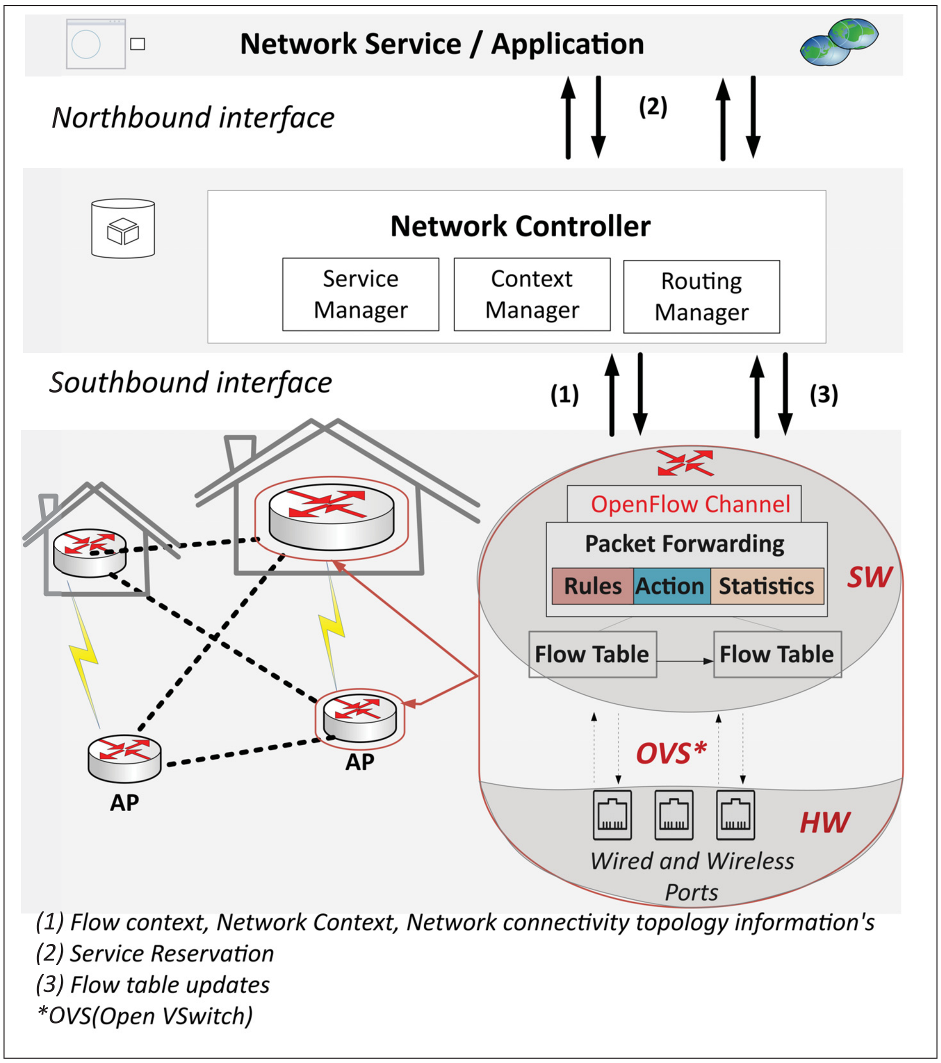


Figure 3.3 SD Smart Community Network Controller and interfaces.

Fig.3.3 shows software defined smart community network controller and interfaces. The communication between the controller and the data plane (APs) is done through a southbound interface like the OpenFlow protocol via a secure OpenFlow channel in order to collect information about topology, link/traffic status and flow/network context. Such channel is also used to update AP flow tables with flow rules defined by the controller. Flow context may include any information characterizing a service flow, which are service type, QoS requirement and burst rate. Network context may include any information charactering the network performance, which are AP state (CPU and memory utilization) and link state (Packet Loss Ration, delay, jitter, and link available bandwidth). The context, link/traffic status and topology information are collected by the controller through analyzing statistical data (table/flow/port /queue/meter levels) of flows and/or through accessing a Management Information Base (MIB). Based on this information, a new route is calculated for each data flow.

We assume that the controller knows whether and where (by which AP/AR) data is cached through a learning process. The problem we address in this paper is to support critical applications in a hybrid wired-wireless network by selecting the best route that meets combined QoS requirements, so path computation must be done under multiple constraints. Thus, the routing problem in the context of the smart community depends on (a) Minimum path cost between all network nodes in terms of delay variation, packet loss and bandwidth usage; (b) delay and packet loss constraints in terms of distance between two neighboring wireless nodes in the network. We assume all wireless links use the same type of communication protocol (e.g. IEEE 802.11ac).

In our formulation, we use $P = \{p_{ij}, i, j = 1, 2, \cdots\}$ to denote the set of all possible paths from node i to node j, B the total available bandwidth in all APs, $Q = \{q_i, i = 1, 2, \ldots\}$ the set of M_c classes of traffics, and Q_i the amount of traffic of class q_i. In this work we are considering only real-time traffic. All used parameters and functions are listed in Table 3.1.

Fig.3.4 illustrates the concept of the caching placement, in which a source s is sending a data m_i through the path p to the destination t. In order to save bandwidth consumption, m_i will firstly be forwarded to an ingress node that will encode and cache this data, and it will finally be decoded at an egress node right before the destination t on the path p. This will avoid sending full sized data between all APs (or ARs) all along the path p. Caching solution will save bandwidth consumption cost as the data will be forwarded from encoded AP (or AR) to decoded

Table 3.1 Notations.

Notations	**Definitions**
$P = \{p_{ij}\}$	Set of all possible paths from node i to node j
$Q = \{q_i\}$, Q_i	Set of class of traffics, bandwidth required by the lass q_i
B, B^*_{ij}, B_{ij}	Total available bandwidth in the system, the real and the theoretical bandwidth associated to (i,j)
$dest_{ij}$	Distance between two neighbor nodes
ls_{ij}, c_{ij},d_{ij}	Packet loss, cost and delay variation within a link (i,j)
$f_u(p)$	Cache utility of the gateway within a path p
$f_c(p)$,$f_D(p)$	Cost and delay variation functions of path p
$f_{loss}(p)$	Packet loss function of path p
$f_{Dest}(p)$	Distance along a path p
$f_a(k)$	The ratio of cached data in an AP (or AR) per its capacity
$f_{BW}(p)$	Total bandwidth along a path p

router in an encoded format. The encoding task is performed by the source node (AP or AR) using a lightweight encoding mechanism (in terms of computational and memory overhead) that generates less-expensive fingerprints (like *FIXED* or *MAXP* approaches Aggarwal *et al.* (2010) Zhang & Ansari (2014)) and performs a simple matching process (like *Chunk-Match* or *REfactor* approaches Shen *et al.* (2011) where both encoding and decoding tasks are performed by the APs).

The total cost of a path p depends on link characteristics such as its type α_{ij} (wired or wireless), cost variation rate $c_i j$, delay $d_i j$, maximum allowed bandwidth B^*_{ij} for both wired and wireless links, and the corresponding loss rate l_{ij}. Each node r_k has a caching memory capacity $\mathcal{C}_k$.

In this paper, we address only smart community's internal traffic optimization problem. Egress traffic is a well-discussed research issue Zhang *et al.* (2016); Jovanović *et al.* (2017); Shakarami & Davoudkhani (2016); Zhao *et al.* (2017), which will not be covered in this work. Also, the scalability issue of the controller in a dense network environment should be considered. In this case we can either add a backup controller Fonseca *et al.* (2012) or perform network segmentation Bozakov & Papadimitriou (2014), so that each controller will manage a particular segment of the network. In the context of this work, a smart community have less than 100 smart homes (each home may have 10 devices), thus, one controller is sufficient to handle all network traffic. Controller scalability issue will therefore be considered in our future work.

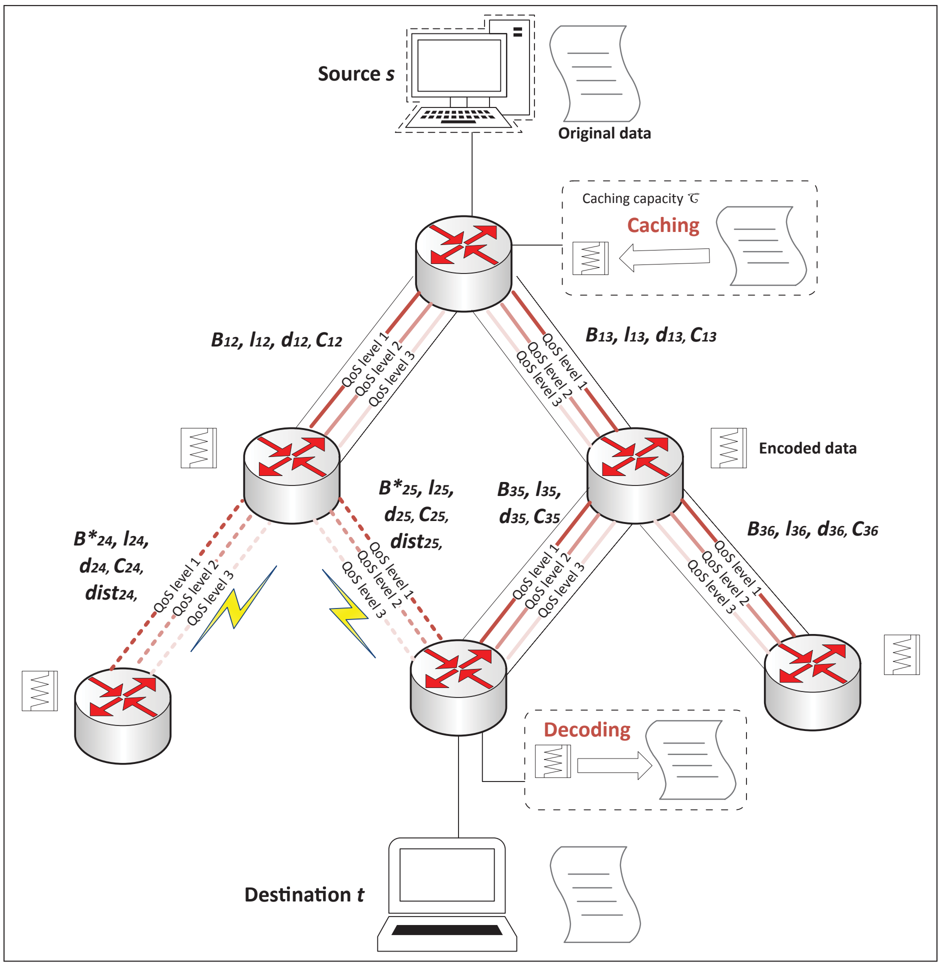


Figure 3.4 System Model.

3.5 QoS Based Routing Problem

Our problem is QoS routing which is formulated as a combination of Constrained Based Shortest Path (CBSP) problem and cache placement problem. It consists of finding an optimal path p from each source-destination pair of nodes (s to t) which minimizes the cost function and then maximizes the cache utility function. It is known as NP-complete Wang & Crowcroft

(1996) which has been addressed in Cui *et al.* (2013); Egilmez *et al.* (2013). The contribution of this paper is improving previous work by considering key factors in smart community context such multi-constrained all-pair QoS-based routing, the reliability of different types of physical accesses and QoS-based caching solution.

The whole network topology is represented as a mixed graph $G(V, E_G)$ that contains a set of undirected subgraphs $G_u(V, E_u)$ for wired links and a set of directed subgraphs $G_d(V, E_d)$ for wireless links. V represents the set of nodes, E_u the set of undirected links and E_d the set of directed links. Each network node in a path p (from source s to destination t), has a cache memory with a limited capacity that caches data m routed over this path. Each data must be cached by only a single AR (or AP) r on a path p.

For each link $(i, j) \in E_G$ we define a cost function $f_c(i, j)$ which is a measure of total link cost based on multiple metrics like link capacity in terms of bandwidth, link memory overhead in terms of node's cache utility, link propagation delay and link packet loss that depends on the type of the link. As there are many types of links (wired, wireless), the path computation can be divided into two parts: path calculation of wireless connections and path calculation of wired connections.

3.5.1 Modeling Packet Loss Rate

We assume that the reliability (e.g., in terms of probability of traffic loss) of a wireless link ls_{ij} is proportional to the distance between two nodes and that the reliability of all wired links is constant Liu *et al.* (2017); Gwak & Kim (2017). Thus, if we increase the distance between two neighbor nodes ($dest_{ij}$), the bandwidth of their link will be reduced by a factor γ (Eq.3.3) and the probability of packet loss ls_{ij} will increase (according to Eq.3.2). A loss rate of link will occur along a path p if the total amount of traffic of all classes $Q_k(ij)$ of traffic exceeds the actual bandwidth of that link B^*_{ij}. For any path p, we define $f_{loss}(p)$ the packet loss function measured as follows.

$$f_{loss}(p) = \prod_{(i,j)\in p} ls_{ij}, \tag{3.1}$$

Where ls_{ij} is the probability of loss on a link (i,j). ls_{ij} is calculated based on the bandwidth B^*_{ij} assigned to that link (Eq.3.2).

$$ls_{ij} = \begin{cases} \frac{\sum_{k\in M_c} Q_{k(ij)} - B^*_{ij}}{\sum_{k\in M_c} Q_{k(ij)}} & \text{if} \quad if(\sum_{k\in M_c} Q_{k(ij)}) > B^*_{ij} \\ 0 & \text{else} \end{cases} \tag{3.2}$$

$$B^*_{ij} = \hat{B_{ij}}(1-\alpha_{ij}) + \alpha_{ij}[\frac{\hat{B_{ij}}}{\gamma.dest_{ij}}] \tag{3.3}$$

α_{ij} is a binary variable that identifies the link type and $\hat{B_{ij}}$ is the bandwidth capacity of the link (i,j).

$$\alpha_{ij} = \begin{cases} 1 & \text{if} \quad B_{ij} \text{ is a wireless link} \\ 0 & \text{if} \quad B_{ij} \text{ is a wired link} \end{cases} \tag{3.4}$$

$0 < \gamma < 1$ is a factor that measures the sensitivity of wireless link according to the length of link. γ is constant in a community because all wireless links use the same communication protocol.

3.5.2 Modeling Path Cost

We define $f_c(p)$ the cost function of a path p as the sum of packet loss and delay variation for each link (Eq.3.5). To enable certain sensitivity in the choice of cost calculation criterion, a variable $0 \leq \beta \leq 1$ is introduced (Eq.3.6). With high value of β, the path cost will depend on the packet loss ls_{ij}. With a low β, the path cost will depend on delay d_{ij}. The path cost function is calculated as follows.

$$f_c(p) = \sum_{(i,j)\in p} c_{ij} \tag{3.5}$$

Where c_{ij} measures the cost of a link (i, j) in terms of packet loss function and delay function $f_D(p)$ (we assume that d_{ij} is a fixed time interval within which a requested data unit passes through a path p) in Eq.3.6.

$$c_{ij} = (1-\beta) * d_{ij} + \beta ls_{ij} \ (0 \leq \beta \leq 1, \forall (i, j) \in P),$$
$$f_D(p) = \sum_{(i,j) \in p} d_{ij}, \tag{3.6}$$

3.5.3 Modeling Gateway Cache Utility

Before sending a data m_i through a path p, the controller checks if this data has already been cached by one of the APs (or ARs) along the path. The cached data can be sent in an encoded format. We define $f_u(p)$ the cache utility of the gateway within a path p as the gain of resources required for sending data m_i along this path (in terms of bandwidth) using an AP (or AR) r_k for caching and decoding this data. The cache utility is calculated as follows.

$$f_u(p) = \sum_{k=1}^{|P|} \sum_{i=1}^{|\theta_i|} e_{ip}(l_i - l'_i) h_{p,k}, \tag{3.7}$$

Where e_{ip} is the number of requesting data m_i to be transferred through the path p, l and l' are respectively the size of decoded and encoded data unit m_i. $h_{p,k}$ is the number of APs and ARs from the source s of p to r_k (k from 1 to total number of APs and ARs in path p) and θ_i : the total number of data m_i going through the path p which is cached and decoded by r_k.

3.6 Problem Formulation

3.6.1 Constraints

A key challenge of this problem is to support critical applications by selecting the best route that meets multiple QoS requirements in the same time. Thus, path calculation must be carried out under several constraints. To minimize the probability of packet loss in Eq.3.1, we define

a threshold L_{max} for the loss function (Eq.3.8) and $Dest_{max}$ (which is the maximum distance between a pair of node in the network) for the sum of all distances $dest_{ij}$ within the path p (Eq.3.9). In addition, the delay in Eq.
labelj1:6 must be lower than a maximum acceptable value D_{max} (Eq.3.10). These constraints are formulated as follows.

$$f_{loss}(p) \leq L_{max} \tag{3.8}$$

$$f_{Dest}(p) = \sum_{(i,j)\in p} dest_{ij} \leq Dest_{max} \tag{3.9}$$

$$f_D(p) \leq D_{max} \tag{3.10}$$

In addition, it is necessary to maintain an acceptable bandwidth for each traffic class and a minimum bandwidth for total traffic. In order to avoid loop in the path, we denote a bandwidth function $f_{BW}(p)$ which is the sum of all bandwidth B^*_{ij} of all links in the path p, must be less than the total APs capacity B (Eq.3.11).

$$\begin{cases} f_{BW}(p) = \sum_{(i,j)\in p} B^*_{ij} \\ f_{BW}(p) \leq B \end{cases} \tag{3.11}$$

On the other hand, the number of data cached by each AP (or AR) r_k must be less than the AP's (or AR) capacity $\mathcal{C}_k$; hence we denote $f_a(k)$ the function of the number of cached data in an AP (or AR) by its capacity as $f_a(k) = \frac{\sum_{i=0}^{M} a_i^k}{\mathcal{C}_k}$. It must be smaller than 1 for each AP (or AR) r_k. a_i^k is a binary variable that determines the AP (or AR) that caches data m_i. $a_i^k = 1$ if the AP (or AR) r_k caches the data m_i. We considered mostly UDP traffic as it is the most common type of flow used in smart community network Sinam *et al.* (2014). The UDP cache size is the same Liu *et al.* (2010). For TCP flows, we can apply the mechanism in Tilli & Kantola (2017) to fragment the packet into small packets in the same size of cache size for UDP. Thus, the constraint in Eq.3.7 for a path p is defined as:

$$f_a(k) \leq 1 \; \forall k \in p \tag{3.12}$$

In reality, AP has a limited capacity of flow table. For example, the size of flow table is 20MbitRen, each flow entry stores the source and destination addresses (each is encoded in 4 bytes word) as well as the QoS metrics (each in 4 bytes). We assume 4 QoS metrics (delay, bandwidth, packet loss and distance between a pair of node), the size of each flow entry is (1+1+4) $\times$ 4=24 bytes=192 bits. Smart community may have 100 smart homes, each home may have 10 devices. If 10% of all devices are activated and communicating to each other in the same time, then we will have a maximum of 100 $\times$100=10000 active flows in the network. The size of the flow table (10MB) is enough to handle 10000 flow entries (10000$\times$192 bits= 1.83 Mbits) within the community network. Thus, we will not consider flow table size as a constraint in our problem.

3.6.2 QoS Based Routing Problem

We model the QoS routing which is formulated as a combination of CBSP problem and cache placement problem. The cost function $f_c(p)$ is subject to the constraints ((3.8), (3.9), (3.10) and (3.11). The utility function $f_u(p)$ is subject to the constraint (3.12). According to this modeling, we must find the optimal pair $(r_{p^*}, m_i)^*$ of AP (or AR) r_{p^*} and the decoding data m_i by r_{p^*} in an optimal path p^* that minimizes the path cost function while maximizing the cache utility and meeting the constraints of delay, distance between the nodes, the total number of data which can be handled by each AP (or AR), and bandwidth capacity of each link lower than that available in the path. We formulate the QoS routing problem by the two following objective functions:

$$p^* = argmin_{f_c} \begin{cases} f_c(p)\ p \in P \\ f_{Dest}(p) \leq Dest_{max} \\ f_D(p) \leq D_{max} \\ f_{BW}(p) \leq B, f_{loss}(p) \leq L_{max} \end{cases} \tag{3.13}$$

$$(r_{p^*}, m_i)^* = argmax_{f_u}\{f_a(k) \leq 1 \forall k \in p\}$$

3.7 QoS Enabling Multi-Constrained Routing

Our solution to solve the QoS based routing problem in (3.11) in smart community networks, while respecting the different constraints in (3.8), (3.9), (3.10) and (3.11), is based on LARAC algorithm Juttner *et al.* (2001). This is a common technique for the calculation of lower bounds, and solving this NP-hard problem.

We propose an algorithm based on LARAC in order to determine the minimal flow costs between all pairs of nodes. In addition, we design an algorithmic solution for QoS routing in a smart community network that takes into account the different types of physical access in terms of packet loss and the cost of using the network in terms of the amount of bandwidth consumed by the APs (or ARs).

3.7.1 H-LARAC: Hybrid LARAC

LARAC algorithm is generally the best heuristic that has been proposed to solve the Constraint-Based Shortest Path (CBSP) problem while minimizing the cost function (in terms of delay variation and packet loss)Guck *et al.* (2017). It consists of finding the shortest path using link cost Egilmez *et al.* (2013). LARAC is used to solve the system modeled by:

$$\left\{\begin{array}{c}\min\ f_c(p)\setminus p\in P\\ \text{subject to: } f_D(p)\le D_{max}\end{array}\right. \rightarrow \left\{\begin{array}{c}\max\ L(\lambda)\\ \text{Subject to: } \lambda\le 0\end{array}\right.$$

Where the Lagrangian function $L(\lambda)$ is defined as, $L(\lambda) = \min\{f_\lambda(p) - \lambda D_{max}\}$ and $f_\lambda(p) = \sum_{(i,j)\in p} c_\lambda(i,j)$ and all QoS parameters are aggregated into a single composite metric as $c_\lambda(i,j) = c_{ij} + \lambda d_{ij}$. The shortest path in a wired connection from the source s to a destination t is the same as that from t to s. However, the wireless connection has different uplink and downlink. To optimize the overall cost under this heterogeneous topology, we duplicate each wired link to obtain a hybrid global topology. We represent this topology as a directed graph, thus, each network node has an even number of edges.

The whole network topology is represented as a directed graph $G = (V, E_G)$ where V represents the set of nodes and E_G the set of directed links.

3.7.2 EH-LARAC: Extended Hybrid LARAC

In order to compute the minimal costs of flows between all pair of nodes in the network, traditional LARAC-based CBSP solutions Egilmez *et al.* (2013), perform repeatedly the LARAC algorithm for each pair of node. In a directed graph, we have $(N-1)$ pair of nodes in downlink and $(N-1)$ pair of nodes in uplink where N is the number of nodes. The complexity of calculating the shortest path between all pair of nodes with the algorithm in Egilmez *et al.* (2013) is $(((N-1)^2)[M + NlogN]^2) \sim O(N^2[N^2 logN + M^2])$ where M is the number of arcs.

In fact, the Dijkstra algorithm can provide only the shortest path from a source to a destination node, making it hard to calculate shortest path between all pairs of nodes in a large network. So, we replaced Dijkstra with Floyd-Warshall algorithm Floyd (1962) that deals with all pairs of nodes rather than repeating Dijkstra for each source/destination node. Dijkstra is rather useful for service providers (that offer services to their subscribers) than for infrastructure providers that should calculate shortest path for all pair nodes (easier with Floyd–Warshall algorithm). In dense graphs (N is significantly smaller than M), the computational complexity of Floyd–Warshall algorithm ($O(N^3)$) is better than that with repeated Dijkstra ($O((N-1)^2(M+NlogN))$ with binary heap implementation).

Algorithm 3.1 EH-LARAC: Extended Hybrid LARAC

```
Input: G, D_max /* G is a directed graph */
Output: Path_opt
Path_c ← ∅, Path_d ← ∅, Path_opt ← ∅;
Path_c(G) ← EFloydWarshall(G,c);
Path_d(G) ← EFloydWarshall(G,d);
for each pair node u = (s,t) in G do
    if (W_cd(u) ≤ D_max) then
        Path_opt(u) ← Path_c(u);
    end
    else if (W_d(u) ≥ D_max) then
        /* no feasible solution */
        Path_opt(u) ← −1;
    end
    else
        while true do
            λ ← (W_c(u) − W_dc(u))/(W_d(u) − W_cd(u));
            r ← Dijkstra(G,u,c_λ);
            if f_λ(r) = f_λ(S_c(u)) then
                Path_opt(u) ← Path_d(u);
                return Path_opt;
            end
            else if (W_cd(u)) ≤ D_max) then
                Path_d(u) ← r;
            end
            else
                Path_c(u) ← r;
            end
        end
    end
end
return Path_opt
```

We improve the H-LARAC by minimizing the repeating instructions for each pair of node using EFloyd-Warshall, an extended version of Floyd-Warshall algorithm that returns not only the shortest paths between all nodes and their shortest-based cost, but also their cost based on others criteria. The running time of the algorithm EH-LARAC is $O(N^3+(N-1)^2[NlogN+M]) \sim O(N^2[(M+NlogN)])$.

We note W_c (or W_d)the minimum weight table between all the node pairs in the graph G using the link costs (delay), provided by the Floyd-Warshall algorithm. EFloydWarshall adds W_{cd} (or W_{dc}) a table of the sum of delays (or costs) between all pair nodes in G with the shortest path using the cost (or delay) of links (it has the same complexity as basic Floyd-Warshall algorithm).

3.7.3 EHM-LARAC: Extended Hybrid multi-constraints LARAC

We extend the EH-LARAC algorithm by adding other constraints to the calculation of the CBSP. This algorithm applies the Lagrangian function to solve the objective function in Eq.3.13. The optimization model becomes therefore:

$$\begin{cases} \min\ f_c(p) \setminus p \in P \\ \text{subject to: } \begin{cases} f_{Dist}(p) \leq Dest_{max}, f_D(p) \leq D_{max} \\ f_{BW}(p) \leq B, f_{loss}(p) \leq L_{max} \end{cases} \end{cases}$$

Then, the problem is defined as a maximization problem: $\begin{cases} \max L(\Lambda) \\ \text{subject to: } \Lambda \subset R^+ \end{cases}$

Where the Lagrangian function $L(\Lambda)$ is defined as,

$$L(\Lambda) = \min\{f_\Lambda(p) - \lambda_1 D_{max} - \lambda_2 Dest_{max} - \lambda_3 B\} \tag{3.14}$$

and

$$f_\Lambda(p,k) = \sum_{(i,j)\in p} c_{\Lambda,k}(i,j) \tag{3.15}$$

All QoS parameters are aggregated into a single composite metric as follows.

$$\begin{cases} c_{\Lambda,k}(i,j) = c_{ij} + \lambda_(\Lambda_k) k_{ij} \\ with\ \lambda_{\Lambda_k} = \begin{cases} \lambda_1 \ if\ k = d \\ \lambda_2 \ if\ k = dest \\ \lambda_3 \ if\ k = bw \\ \lambda_4 \ if\ k = loss \end{cases} \end{cases} \tag{3.16}$$

The modified algorithm EHM-LARAC (illustrated in Algorithm 3.2) finds the shortest paths between all pair of nodes based on each criterion (line 3). $Path_i(G)$ at line 2, contains all the shortest paths $(W_i, S_i, W_{id}, W_{idest}, W_{ibw}, W_{iloss})$ in the graph G according to the metric $i = c, d, dest, bandwidth, loss$. $Path_{opt}$ is the best feasible (or near-optimal) path we are looking for, as there is no optimal path in a Lagrangian relaxation based heuristic solution. LARAC algorithm gives a lower bound on the theoretical optimal solution of CSP problem Juttner *et al.* (2001). We assume that the optimality of a path is evaluated based on metric i. $Path_i(G,s)$ contains the shortest paths of the graph G from node s to all the nodes, according to the different criteria. W_{cd}(or W_{dc} or W_{cdest} or W_{destc} or W_{cbw} or W_{bwc} or W_{closs} or W_{lossc}) is the sum of delays (or cost/ distance/ bandwidth /loss) between all pair of nodes in G with the shortest path using the cost (or delay/ distance/ bandwidth/ loss) of link. The optimal value of each Lagrange multiplier (λ_1, λ_2, λ_3 et λ_4), in line 11, is determined by solving the following linear equations for each pair of nodes:

$$\begin{cases} f_c(S_c,S_d) = -\lambda_1 f_d(S_c,S_d) \\ f_c(S_c,S_{dest}) = -\lambda_2 f_{dest}(S_c,S_{dest}) \\ f_c(S_c,S_{bw}) = -\lambda_3 f_{bw}(S_c,S_{bw}) \\ f_c(S_c,S_{loss}) = -\lambda_4 f_{loss}(S_c,S_{loss}) \end{cases} \rightarrow \begin{cases} \begin{cases} f_c(S_c) = -\lambda_1 f_d(S_c) \\ f_c(S_d) = -\lambda_1 f_d(S_d) \end{cases} \\ \begin{cases} f_c(S_c) = -\lambda_2 f_{dest}(S_c) \\ f_c(S_{dest}) = -\lambda_2 f_{dest}(S_{dest}) \end{cases} \\ \begin{cases} f_c(S_c) = -\lambda_2 f_{bw}(S_c) \\ f_c(S_{bw}) = -\lambda_3 f_{bw}(S_{bw}) \end{cases} \\ \begin{cases} f_c(S_c) = -\lambda_4 f_{loss}(S_c) \\ f_c(S_{loss}) = -\lambda_4 f_{loss}(S_{loss}) \end{cases} \end{cases}$$

Details of resolve function at line 11 in Algorithm 3.2 is follows.

$$\begin{cases} \lambda_1 = \frac{f_c(S_c)-f_c(S_d)}{f_d(S_d)-f_d(S_c)} \\ \lambda_2 = \frac{f_c(S_c)-f_c(S_{dest})}{f_{dest}(S_{dest})-f_{dest}(S_c)} \\ \lambda_3 = \frac{f_c(S_c)-f_c(S_{bw})}{f_{bw}(S_{bw})-f_{bw}(S_c)} \\ \lambda_4 = \frac{f_c(S_c)-f_c(S_{loss})}{f_{loss}(S_{loss})-f_{loss}(S_c)} \end{cases} \rightarrow \begin{cases} \lambda_1 = \frac{W_c(u)-W_{dc}(u)}{W_d(u)-W_{cd}(u)} \\ \lambda_2 = \frac{W_c(u)-W_{destc}(u)}{W_{dest}(u)-W_{cdest}(u)} \\ \lambda_3 = \frac{W_c(u)-W_{bwc}(u)}{W_{bw}(u)-W_{cbw}(u)} \\ \lambda_4 = \frac{W_c(u)-W_{lossc}(u)}{W_{loss}(u)-W_{closs}(u} \end{cases}$$

If the resulting optimal path does not satisfy all the constraints, a new path is determined iteratively by substitution (see Algorithm 3.3).

3.8 Maximized Caching Algorithm

Our solution to solve the QoS based caching problem (Eq.3.13) in smart community networks while respecting the constraint (Eq.3.12) is based on Offline Traffic Redundancy Elimination (OFTRE) algorithm Cui *et al.* (2013). This algorithm looks for the best pair of APs (or ARs) and its cached data that maximizes the total cache utility of all paths in the network. However, in the context of a community network we need to calculate the path between each source-destination pair of nodes. Thus, we improve the OFTRE algorithm in Cui *et al.* (2013) by maximizing the cache utility for each path rather than for all paths, which makes our problem more granular than OFTRE, and then more challenging. We apply the Path-based OFTRE

Algorithm 3.2 EHM-LARAC: Extended Hybrid multi-constraints LARAC

Input: G, L_{max}, D_{max}, $Dest_{max}$, B
Output: $Path_{opt}$
`/* G is a directed graph */`
$Path_c \leftarrow \emptyset$, $Path_d \leftarrow \emptyset$, $Path_{dest} \leftarrow \emptyset$, $Path_{loss} \leftarrow \emptyset$, $Path_{opt} \leftarrow \emptyset$;
findPCC ($Path_c$, $Path_d$, $Path_{dest}$, $Path_{bw}$, $Path_{loss}$, G);
for *each pair node* $u = (s,t)$ *in* G **do**
  if $(W_{cd}(u)) \leq D_{max})$ *and* $(W_{cdest}(u)) \leq Dest_{max})$ *and* $(W_{cbw}(u)) \leq B)$ *and* $(W_{closs}(u)) \leq L_{max})$ **then**
    $Path_{opt}(u) \leftarrow Path_c(u)$;
  end
  else if $(W_d(u)) \geq D_{max})$ *or* $(W_dest(u)) \geq Dest_{max})$ *or* $(W_bw(u)) \geq B)$ *or* $(W_{loss}(u)) \geq L_{max})$ **then**
    `/* no feasible solution */`
    $Path_{opt}(u) \leftarrow -1$;
  end
  else
    while *true* **do**
      $\Lambda_{opt} \leftarrow$ **resolve**(u, $Path_i(G)$);
      $r_{c_\Lambda} \leftarrow Dijkstra(G, \Lambda_{opt})$;
      if $f_\lambda(r) = f_\lambda(S_c(u))$ **then**
        $Path_{opt}(u) \leftarrow Path_c(u)$;
        break;
      end
      else if $(W_{ci}(u)) \leq i_{max})$ **then**
        `/* for all parameters */`
        update ($Path_i(u)$, r_{c_Λ}, i_{max}) `/* for all parameters */`
      end
      else
        $Path_c(u) \leftarrow r_{c_\Lambda}$;
      end
    end
  end
end
return $Path_{opt}$

algorithm (P-OFTRE) to the optimal set of paths p^*, provided by our EHM-LARAC algorithm, in order to maximize the utility of their AP's (or AR) cache capacity by minimizing data redundancy on each path.

Algorithm 3.3 Updating routing path

Input: $Path_d(u)$, $Path_{dest}(u)$, $Path_{bw}(u)$, $Path_{loss}(u)$, r_{c_Λ}, D_{max}, r_{dest}, $Dest_{max}$, M_{max}, L_{max}
Output: *Path updated*
if $(W_{cd}(u)) \leq D_{max})$ **then**
  $Path_d(u) \leftarrow r_{c_\Lambda}$;
end
if $(W_{cdest}(u)) \leq Dest_{max})$ **then**
  $Path_{dest}(u) \leftarrow r_{c_\Lambda}$;
end
if $(W_{cbw}(u)) \leq B_{max})$ **then**
  $Path_{bw}(u) \leftarrow r_{c_\Lambda}$;
end
if $(W_{closs}(u)) \leq L_{max})$ **then**
  $Path_{loss}(u) \leftarrow r_{c_\Lambda}$;
end

In the modified algorithm P-OFTRE (illustrated in Algorithm 3.4), $D = \{d_1, d_2 \ldots d_{|D|}\}$ is the set of transferred data, $E = (e_{ip})_{|D|*|P|}$ is the data assignment matrix in each path, $Path_{opt}$ is the optimal path provided by EHM-LARAC and $\mathcal{C}_k$ is the maximum capacity of each AP (or AR).

The proposed algorithm generates the caching matrix A (line 2) for each data-AP (or AR) pair (from line 3 to 28) that meets the constraints in Eq.3.13, and the decoding AP (or AR) assignment matrix R for each data-path pair (from line 29 to 32). The algorithm initializes the caching assigning matrix A and the cache capacity for all APs (or ARs) along the optimal path between each pair of nodes in the graph G, then calculates the cache utility for each data-AP (or AR) pair on the path as described in Eq.3.7. A cache utility of on a zero-capacity caching AP (or AR) will be equal to 0 (from line 22 to 26). The AP (or AR) that maximizes cache utility for a data-path pair (d_i, p) is the optimal AP (or AR) that caches a data d_i through p. Depending on the data assignment matrix E, the cache utility will be updated for each AP (or AR) on the path p, other than the optimal AP (or AR)(from line 12 to 21).

Finally, Algorithm 3.5 illustrates the QoS-Aware Software-Defined Routing (QASDN) algorithm that combines the two algorithms EHM-LARAC and P-OPTR to compute optimal path regarding different metrics between all pair of nodes, and assign optimal APs (or ARs) to cache data on these paths. The controller of smart community will implement the QASDN algorithm to route traffic for critical-mission applications.

Algorithm 3.5 QASDN: QoS-Aware Software-Defined Routing

Input: G, L_{max}, D_{max}, $Dest_{max}$, B, D, E, $\{\mathcal{C}_k\}$

```
/* G is a directed graph */
/* A is caching assignement matrix */
/* R is a matrix of decoding APs (or ARs) for all paths in G */
```

$Path_{opt} \leftarrow \emptyset$;

$A = (a_{ik})_{|D|*|R|}$, $R = r_1, r_2 ... r_{|R|}$;

$Path_{opt} =$ EHM-LARAC $(G, L_{max}, D_{max}, Dest_{max}, B)$;

$(A, R) =$P-OFTRE $(G, D, E, Pathopt, \{\mathcal{C}_k\})$;

Table 3.2 presents a theorical comparison between QASDN and traditionnal LARAC-based CBSP.

Table 3.2 Theorical comparison of QASDN and LARAC-based CBSP.

Theorical comparison	**LARAC-based CBSP**	**QASDN**
Wired-wireless routing		✓
All-pair of node routing		✓
Meeting delay constraint	✓	✓
Meeting distance constraint		✓
Meeting bandwidth constraint		✓
Meeting packet loss constraint		✓
Maximizing cache utility function		✓
Computational complexity of finding the best path	$O(N^2[N^2 logN + M^2])$	$O(N^2[(M + NlogN)])$
Objective function	$p^*(s,t) = argmin_{f_c} \begin{cases} f_c(p(s,t)) \\ f_D(p(s,t)) \leq D_{max} \end{cases}$	$p^* = argmin_{f_c} \begin{cases} f_c(p)\ p \in P \\ f_{Dest}(p) \leq Dest_{max} \\ f_D(p) \leq D_{max} \\ f_{BW}(p) \leq B \\ f_{loss}(p) \leq L_{max} \end{cases}$ $(r_{p^*}, m_i)^* = argmax_{f_u} \{f_a(k) \leq 1 \forall k \in p\}$

3.9 Performance Evaluation

To evaluate the performance of the proposed QASDN algorithm, we build a simulation with 14 fully meshed network topologies containing from 2 to 400 nodes. Thus, there are at most 160000 paths in the simulating networks. The threshold fixed for each criterion ($D_{max}, Dest_{max}$,

B_{max}, L_{max}) corresponds to the maximum cost of the shortest path based on that criteria. We set the maximum delay variation from 0.3 to 2ms, the maximum tolerated distance from 8 to 17m, the maximum bandwidth variation from 5 to 10 Mbps, and the maximum tolerated loss rate from 0.6 to 1%. For cache utility calculation, we evaluate our solution with randomly generated data D and delivery count matrix E. In the scenario considered in this paper, the sensitivity of wireless link γ is constant because all wireless links use the same type of communication protocol IEEE 802.11ac (see Section 3), thus, we set it to 0.2 in Eq.3.3 according to the maximum range achieved by IEEE 802.11ac in Dianu *et al.* (2014). However, we can vary the scale factor β in Eq.3.6 to make the route selection more sensitive to either loss or delay variation depending on the characteristics of the network traffic. Since we target delay-sensitive applications in smart community network (the most challenging issue faced by community network) as discussed in Section 1, we set β to 0.1 to make the route selection more sensitive to delay variation. We set the length of original and encoded data unit to 200 and 50 respectively. We randomly set the type of links (wireless or wired). Table 3.3 describes our experimental setup.

We plot the curve of the percentage of paths under threshold with QASDN (Fig.3.5). We note that the majority of paths under threshold for each criterion can reach to 100 %, however, it decreases when we increase the size of topology. The average number of paths that meets the loss and the delay threshold (thr) is kept at a good rate (53%) for up to 50 nodes.

In Fig.3.6, we also compare the performance of our algorithm QASDN (Algorithm QASDN) and the traditional CBSP algorithm that uses LARAC as solution to solve the CBSP problem (LARAC-based CBSP). In the following figures, we simply use “CBSP” for “LARAC-based CBSP”. QASDN is compared with LARAC-based CBSP algorithm in terms of: a) the percentage of paths that meets all constraints for different numbers of nodes (Fig.3.6(a)), b) the number of paths that fulfill each constraint obtained with QASDN over those obtained with LARAC-based CBSP for 14 tests (Fig.3.6(b)), and c) the cache utility (CacheU) in Mbps obtained with QASDN and CBSP for different numbers of nodes (Fig.3.6(c)).

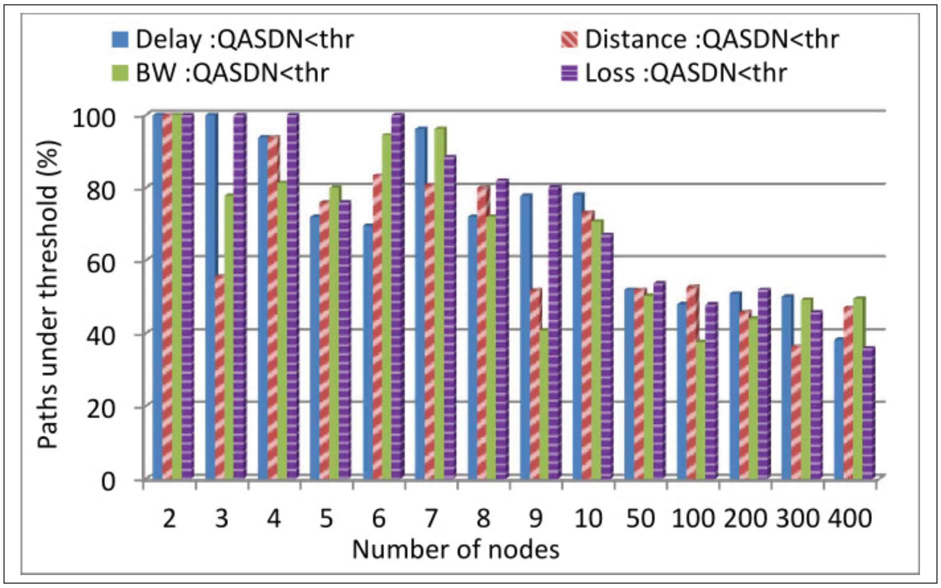
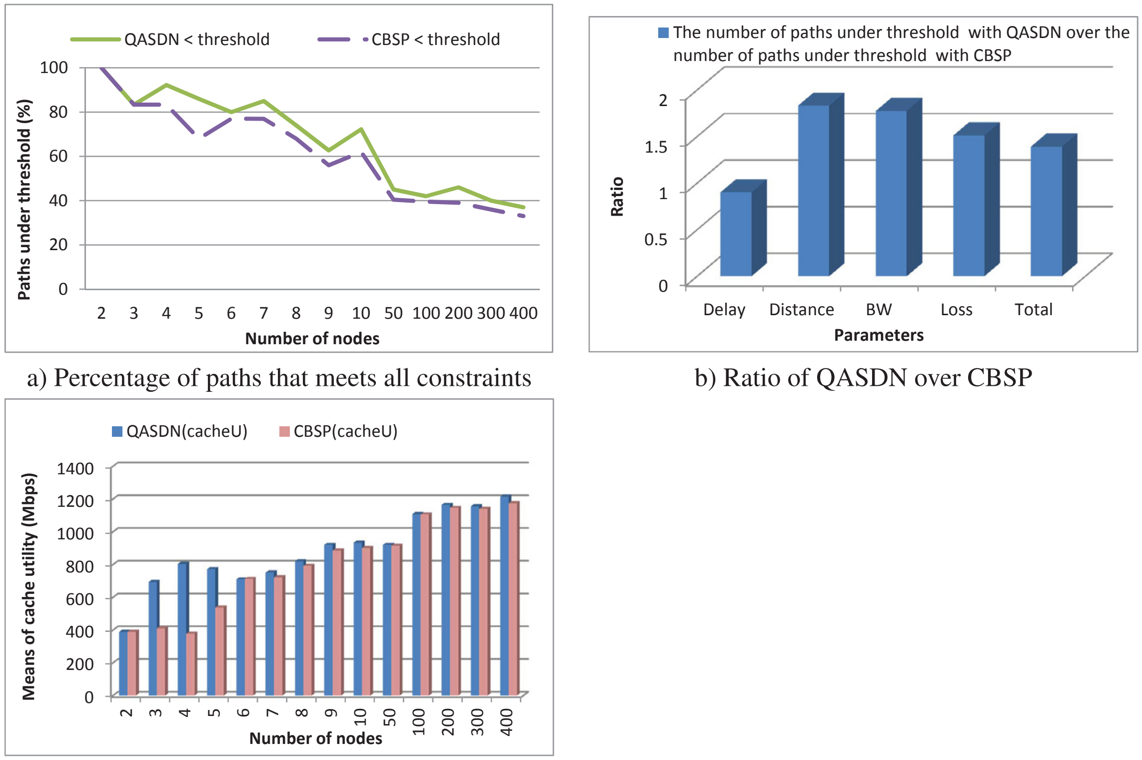


Figure 3.5 Success rate of QASDN by number of nodes.

Table 3.3 Experimental Setup.

Parameter	Value
Number of topologies	14
Number of nodes	2-400
Number of paths	2-160000
Link Delay	random.uniform(0.1, 2.1)(ms)
Link Distance	random.randint(1, 20)(m)
Link Type	random.choice(wireless, wired)
Number of data D	random.randint(1, 200)
Number of data assignment to each AP (or AR)	random.randint(1, 5)
Length of original data (l)	200 bytes
Length of encoded data (l')	50 bytes

Fig.3.6 shows the proposed QASDN algorithm outperforms the LARAC-based CBSP algorithm for the majority of criteria, with 83% for distance, 77% for bandwidth and 51% for loss,



a) Percentage of paths that meets all constraints

b) Ratio of QASDN over CBSP

c) Cache utility for different nodes

Figure 3.6 QASDN vs CBSP.

while increasing the delay variation to about 10%. We note that LARAC-based CBSP algorithm returns the optimal path for a single criterion (the delay) while increasing significantly the cost of the other criteria. On the other hand, QASDN algorithm maintains the four parameters in an acceptable rate. We can see also that QASDN algorithm can provide a gain in AP (or AR) resources up to 90%.

Specifically, we study the performance of the proposed QASDN regarding the following criteria of the resulting optimal path: delay, bandwidth (BW_{max} is the total APs bandwidth capacity B (see Eq.3.11)), distance and loss. We plot these criteria in Figures 3.7 and 3.8. Figures 3.7(a) and 3.8(a) show when we increase the number of nodes, the difference between the delay of paths compute by QASDN and those by LARAC-based CBSP decreases and the two curves will have almost the same shape. On the other hand, QASDN decreases significantly the bandwidth consumption for most of paths (down to 100% in Fig.3.7(b) and to 88% in Fig.3.8(b)).

Distance based shortest path ($Path_{dist}$) still has the minimum distance, however, QASDN outperforms LARAC-based CBSP by decreasing the distance up to 84% in Fig.3.7(c) and up to 60% in Fig.3.8(c). The packet loss is considerably decreased with an improvement of up to 48% with 5 nodes in Fig.3.7(d) and 60% with 10 nodes in Fig.3.8(d) maintaining the majority of paths under the maximum tolerated loss variation

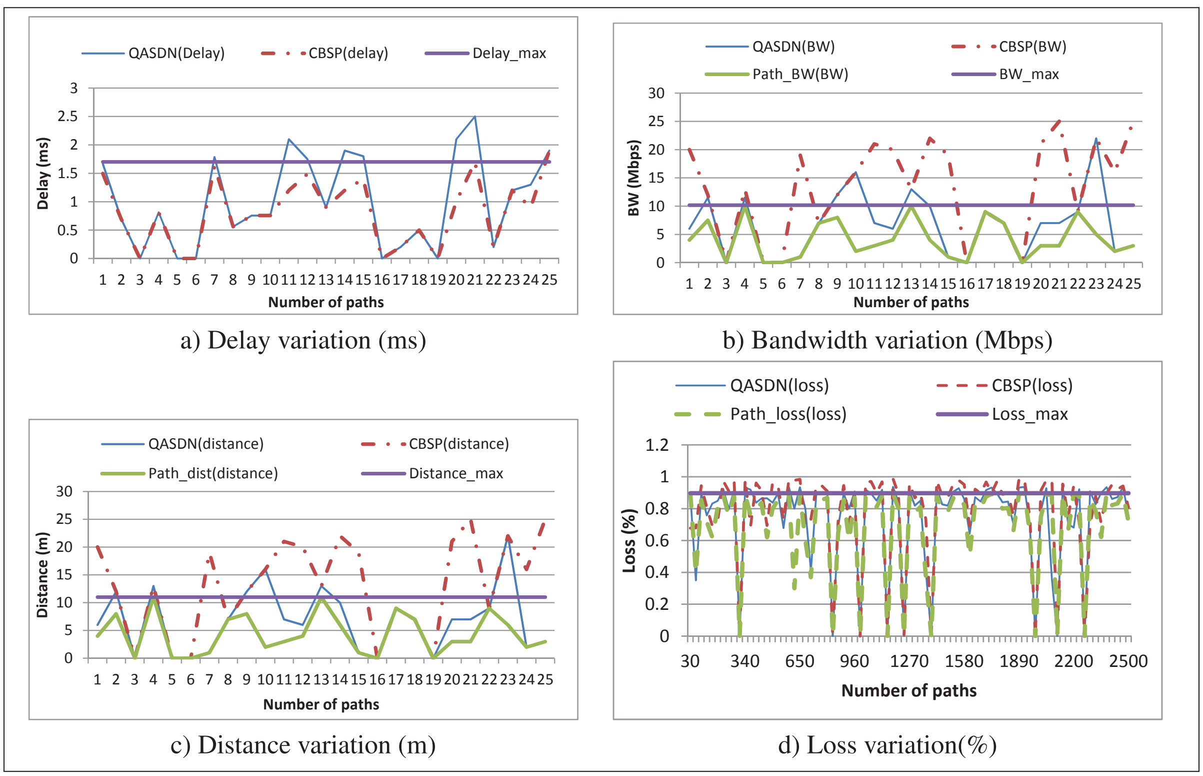
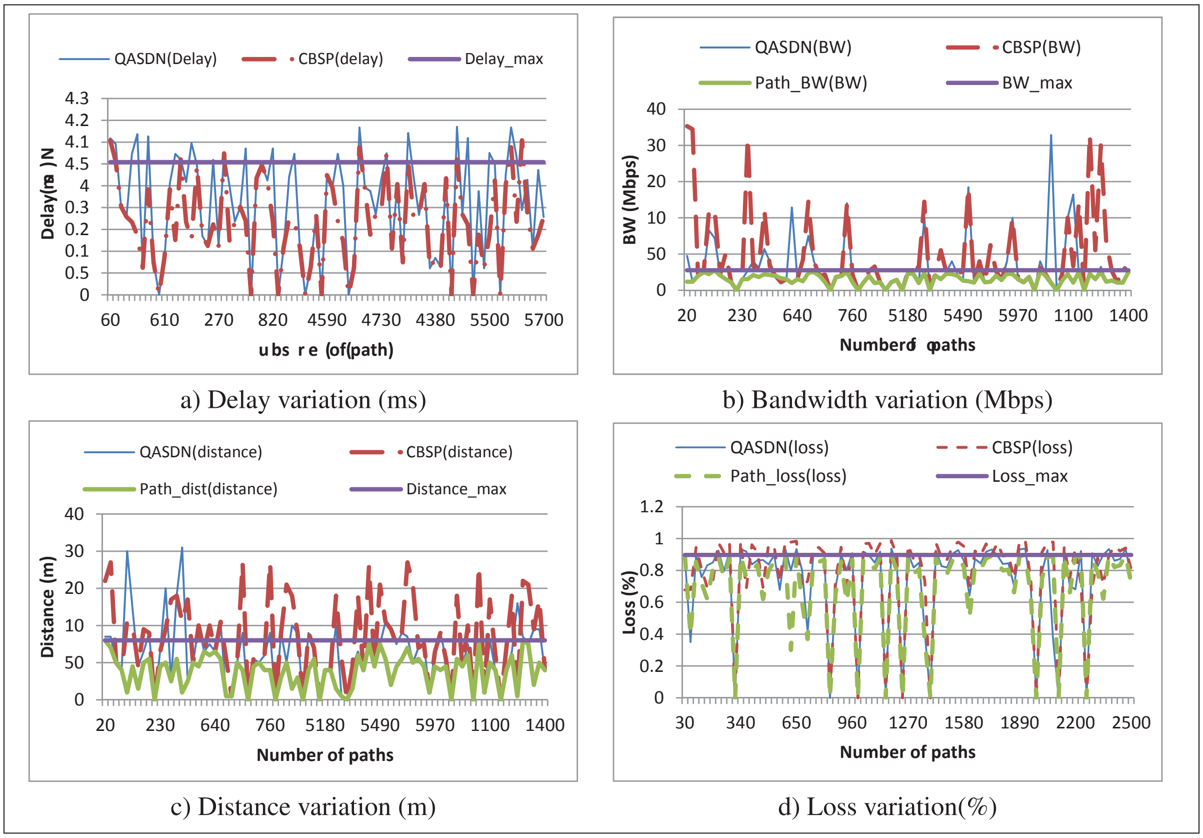


Figure 3.7 Variation of QoS parameters for 5 nodes.

In Fig.3.9, the effect of varying weight factors, β and γ in the performance of the proposed algorithm is shown. We plot the mean values of delay (in ms) and loss (in %) of a path resulting from QASDN for 10 nodes (corresponding to the nodes in Fig.3.8) with different values of β (from 0 to 1) and γ (from 0.001 to 0.999). In Fig.3.9(a), increasing the scale factor β (when γ is fixed) will increase the delay and decrease the packet loss. In fact, with a higher value of β in Eq.3.6, the path selection will be more sensitive to loss and with a low value of β, the total path cost depends more on delay. In Fig.3.9(b), both the delay and the packet loss increase



a) Delay variation (ms)

b) Bandwidth variation (Mbps)

c) Distance variation (m)

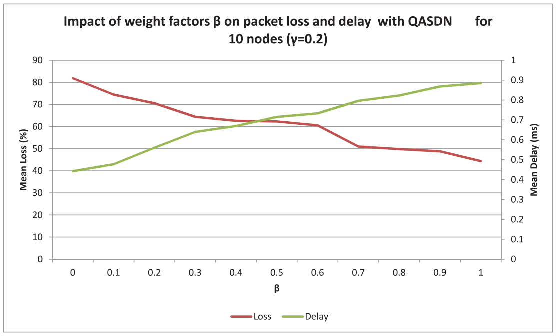
d) Loss variation(%)

Figure 3.8 Variation of QoS parameters for 10 nodes.

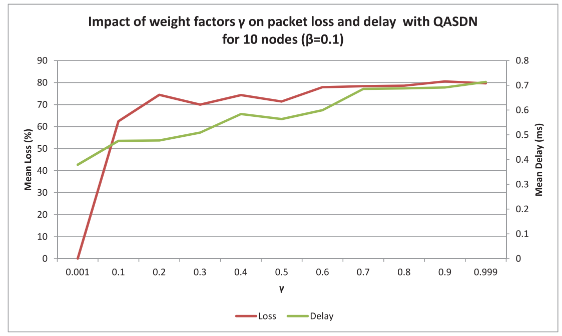
with higher value of γ (maximum loss for $\gamma = 0.999$ and 0 % loss for $\gamma = 0.001$) when β is fixed.

3.10 Conclusion and Future Work

In this paper, we proposed an analytical framework for optimizing dynamic QoS-based data streams in a software-defined smart community network. We formulated a QoS-based routing optimization problem as constrained shortest path problem, and then proposed an optimized solution to determine minimal cost flows between all pairs of nodes in smart community network, taking into account the different types of physical accesses and combined network QoS (delay, bandwidth, loss and distance).



a) Impact of the weight factor β on packet loss and delay with QASDN for 10 nodes (γ=0.2)



b) Impact of the weight factor γ on packet loss and delay with QASDN for 10 nodes (β=0.1)

Figure 3.9 Impact of the weight factors β and γ on packet loss and delay with QASDN for 10 nodes.

We tested our solution in 14 topologies with a random number of nodes from 2 to 400 nodes and we compared it to the traditional LARAC-based CBSP algorithm for each criterion. Our experimental results demonstrated that the proposed algorithm outperforms the traditional shortest cost based algorithm in almost the totality of constraints.

However, this work has not yet considered the trade-off among the criteria. For example, delay could increase when loss, bandwidth and distance decrease. This issue would be solved by applying a traffic differentiation method. That is, delay sensitive traffic would be treated in a higher priority by APs (or ARs). This will be done in our future work. In addition, our current solution addresses only smart community's internal traffic optimization problem, which will also be extended to incorporate the egress router of smart community and its traffic engineering policies.

3.11 Acknowledgment

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Algorithm 3.4 P-OFTRE: Path-based Offline Traffic Redundancy Elimination

Input: *G, D, E,* $Path_{opt}$, $\{\mathcal{C}_k\}$
Output: (A,R)
/* G is a directed graph */
$A = (a_{ik})_{|D|*|R|}$, $R = r_1, r_2 ... r_{|R|}$;
// *R is the set of APS (or ARs)*;
// $A[i][k] = 1$ *if* r_k *caches* d_i ;
// $R[i][p] = r_k$ *if* r_k *is the decoding AP (or AR) of* d_i *in* p;
for *each pair node* $u = (s,t)$ *in G* **do**
    for *each AP (or AR)* r_k *in* $Path_{opt}[u] = p$ **do**
        $r_k.capacity = \mathcal{C}_k$;
        for *each data* d_i *in D* **do**
            $A[i][k] = 0$;
            $u\ (d_i, r_k, p) = E[i][p](l_i - l'_i).h_{p,k}$;
        end
    end
    Mark all data-path pairs (d_i, p) as "Unassigned" ;
    while $\sum_{k=0}^{|R|} r_k.capacity \neq 0$ **do**
        Select (d_i, r_k) that maximizes **u** (d_i, r_k, p) with r_k.capacity $\neq o$;
        $A[i][k] = 1$ // r_k *caches* d_i ;
        r_k.capacity-r_k.capacity -1 ;
        if $E[i][p] \neq 0$ *and* (d_i, p) *is 'Unassigned'* **then**
            mark pair (d_i, p) as 'Assigned' ;
            for *each AP (or AR)* $r_h \neq r_k$ *in p* **do**
                $\mathbf{u}\ (d_i, r_h, p) = \mathbf{u}(d_i, r_h, p) - \mathbf{u}(d_i, r_k, p)$ /* refresh cache utility of other APs (or ARs) */
            end
        end
        if $r_k.capacity = 0$ **then**
            for *each* d_i **do**
                $\mathbf{u}(d + i, r + k, p) = 0$;
            end
        end
    end
end
for *each* (d_i, p) **do**
    $m_{r_k} = argmax_{r_k}(h_{p,k})$ where r_k in p and $A[i][k] = 1$;
    $R[i][p] = r_{m_{r_k}}$ //*is the decoding AP (or AR) of* (d_i, p) ;
end
return (A,R)

CHAPTER 4

DYNAMIC QOE/QOS-AWARE QUEUING FOR HETEROGENEOUS TRAFFIC IN SMART HOME

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4.1 Abstract

Smart home gateways have to forward multi-sourced network traffic generated with different distributions and with different Quality of Service (QoS) requirements. Most of the current QoS-aware scheduling methods consider only the conventional priority metrics based on the IP Type of Service (ToS) field to make decision for bandwidth allocation. Such priority-based scheduling methods are not optimal to provide both QoS and Quality of Experience (QoE) since higher priority traffic do not necessarily require higher stringent delay than lower-priority traffic (for example traffics generated from medical sensors get higher priority than packets generated from streaming devices that require a lower maximum delay compared to the periodic medical sensors). To solve the gaps between QoS and QoE, we propose a new queuing model for QoS-level Pair traffic with mixed arrival distributions in Smart Home network (QP-SH) to make dynamic QoS-aware scheduling decisions which meet delay requirements of all traffic while preserves their degrees of criticality. A new metric which combines the ToS field and the maximum number of packets that can be processed by the system's service during the maximum required delay, is defined. Our experiments show the proposed solution achieves an improvement of 15% of packets that meet their priorities and 40% of packets that meet their maximum delays as well as an increase of 25% of packets processed in the system.

Keywords: Quality of service, quality of experience, smart home, traffic scheduling optimization.

4.2 Introduction

A smart home network is a network that connects sensors, home appliances, and intelligent devices that react with each other with user instructions or system provider (for example remote control of devices or intelligent heating systems automatically adapting to outdoor temperature)Marikyan *et al.* (2019). Smart home networks are evolving rapidly to include heterogeneous physical access (both wired and wireless) and a large number of smart devices that generate different types of traffic with different distributions. Also, a variety of applications (VoIP, messaging, video, etc.) with different requirements is putting more constraints in smart home traffic scheduling such as congestion and delay. This requires automated management of traffic loads within the home gateway by offering more than one priority class. From the perspective of Internet Service Providers (ISP), this priority is decided based on bandwidth requirements for critical applications using IP ToS field Pfeffer (2019), however, from the perspective of the home user, the priority is decided based on delay requirement especially for video streaming applications. For example, regarding criticality, packets generated from a fire detector or medical sensors get higher service priority than packets generated from streaming devices, and regarding the delay, streaming devices (that have video bitrates between 400 kbps and 14,000 kbps IBM (2018)) require a lower maximum delay compared to periodic sensing objects as medical sensors (with sensing rate between 12 bps and 12 kbps). Thus, scheduling with QoS (quality of service) in the context of the smart home network should consider specific metrics that reflect the specific demand of the traffic, besides the conventional priority level metric, which is based even on IP ToS field or user preferences. Then, each traffic application must be mapped to both priority class and delay-sensitive class and processed by a proper scheduling discipline to ensure that it meets their QoS requirements regarding criticality and QoE requirements regarding the delay to avoid local network congestion. The most challenging issue faced by smart home gateway is to provide both ISP and home users satisfactions in terms of QoS and

Quality of Experience (QoE) especially to delay-sensitive applications Zhang (2018); Zhang *et al.* (2018); Li *et al.* (2016a); Premarathne *et al.* (2017a) through finding an automatic way to schedule multi-sourced packets while considering their degree of criticality and meeting their maximum required delay. Most of the previous work that target scheduling with QoS problems Benacer *et al.* (2018); Shakir & Rajesh (2017); Anand & de Veciana (2017); Bakhshi & Ghita (2016); Bozkurt & Benson (2016); Yang *et al.* (2018); Abuteir *et al.* (2016); Zeng *et al.* (2018); Butt *et al.* (2018); Zheng *et al.* (2017); Chaabnia & Meddeb (2018) cannot be efficiently applied in a smart home network since they do not consider the impact that prioritizing specific traffic based only on static metrics like TOS field or user-defined preferences may have on other network traffic (lower-priority traffic may miss their maximum allowed delay when prioritizing higher priority traffic having a higher upper-delay bound).

In this paper, we propose a dynamic model for optimizing packet scheduling in the smart home network with mixed arrival distributions while considering both the critical nature of the application and the maximum allowed delay. The contribution of this paper includes a new dynamic queuing model for smart home network traffic generated by heterogeneous sources, which increases the number of packets that meet their deadline while preserves their degree of criticality. The rest of the paper is organized as follows. We will discuss related studies on QoS based scheduling in Section 4.3. In Section 4.4, we will describe the smart home traffic scheduling with QoS constraints. QoS scheduling problem is presented in Section 4.5. Section 4.6 describes the proposed queuing model for QoS-level Pair Heterogeneous-sourced traffic in the smart home network (QP-SH). Performance results of our solution are provided in Section 4.7. Finally, we draw conclusions and present future work.

4.3 Related Work

Many scheduling algorithms have been proposed in previous work to manage different type of network traffic (summarized in Table.4.1). Benacer *et al.* (2018) contributed a high capacity Hybrid Priority Queuing (HPQ) for high-speed network devices. HPQ is a fixed priority algorithm based on Priority Queuing (PQ), which considers the priority order of inserting packets.

Shakir & Rajesh (2017) contributed a two-level queuing model that considers the theoretical delay to provide QoS requirements in LTE networks. In the first layer queuing, packets are sorted based on their size, their expected departure time and the service time; then, they are scheduled to form calendar discs using a weighted fair queuing algorithm (WFQ). In the second layer queuing, the calendar discs are sorted based on their frequency bands and their corresponding packets are selected using Weighted round-robin algorithm (WRR), a generated form of Fair Queuing (FQ), which allows, at each scheduling round, en/de-queuing a certain number of packets (weights) from each queue. Anand & de Veciana (2017) contributed a multi-class scheduler which optimizes end-user QoE based on mean flow delay in wireless networks. Their solution uses a weighted Gittins index scheduler to optimize resources allocation for different classes of applications according to their sensitivity towards the mean delay. Bakhshi & Ghita (2016) proposed a queuing model that considers user-defined profile priorities to optimize bandwidth allocation in-home network. Their solution is based on Software Defined Network (SDN) technology to calculate user-profiles in a central controller which resides on the cloud and push the resulting rules on home gateway. The authors evaluate their solution using multimedia and video streaming applications. Their solution has shown a good performance in terms of latency and packet loss for only a selected set of high priority users.

Bozkurt & Benson (2016) contributed a context-aware scheduling discipline which prioritizes home network traffics based on the currently active applications and devices. Yang *et al.* (2018) proposed a cloud-based scheduling solution to prioritize home applications using packet inspection. The authors evaluate their solution using video streaming applications. Their architecture risks to let low-high priority queues starve since it considers only the static nature of priority assignments. Abuteir *et al.* (2016) contributed a Wireless Network Assisted Video Streaming (WNAVS) framework which relies on SDN technology to schedule home packets based on real-time bandwidth allocation and network traffic statistics. However, their solution focuses only on one type of home application which is not the case for real home network traffic. Hsieh & Hou (2018) proposed an online scheduler which maximizes wireless network utility based on the QoE of each flow. The authors used the duration of video playback interruption to optimize QoE for video-on-demand applications under heavy-traffic conditions. Their solution proposed to schedule the client with the largest data rate in each scheduling period if there are no ties. If a tier occurs, the selected client is the one with the smallest product of its weight and the difference between the total amount of received data and the total number of bits that should have been played if there is no video interruption. Each client is assigned a weight by the access point that reflects its class of service.

Zeng *et al.* (2018) contributed a scheduling scheme for Vehicle Ad hoc NETworks which increases the QoE of charging and discharging electric vehicles while optimizing the load capacity of the power grid. Each electric vehicle is matched to the charging station that maximizes its charging utility and has at least one free interface. Electric vehicles may cooperate in the same charging station by selling their electricities (discharging) to vehicles with low battery levels. The cooperative electric vehicles charging and discharging is scheduled using a Pareto Optimal Matching Algorithm. Butt *et al.* (2018) proposed a cross-layer scheduling framework over fading channels which guarantees the minimum QoS requirements in terms of energy consumption while satisfying the QoE in terms of loss tolerance for loss-tolerant applications in 5G wireless network. The authors used the Markov decision process to model their scheduling problem, and they used stochastic optimization techniques to solve it. Zheng *et al.* (2017) proposed a task layer scheduling scheme to improve QoE in terms of the quality of the transmission of a group of packets (called task) rather than the quality of the link in wireless networks. Each link can support many tasks from differents class of services with differents delay constraints. Their solution calculates the remaining time of each task and each link. Then, the link with the least remaining time is selected to schedule tasks with the fewest packets. Authors considered the QoE using the global throughput and the QoS using maximum delay for each class of service. Fan & Zhao (2018) contributed a cross-layer scheduling scheme for video streaming which considers the average end-to-end delay and the frame buffer level at the destination nodes to improve both QoS and QoE in wireless Ad hoc networks. The authors used the Lyapunov optimization framework to solve the optimization problem and proposed a distributed media access control algorithm to reduce computational complexity.

Chaabnia & Meddeb (2018) contributed a new distributed model for home network traffic prioritization based on SDN technology. The authors implemented two-level slicing strategies; control-level slicing where traffic is prioritized based on bandwidth requirements and data plane level slicing where traffic is prioritized based on the type of application. Each data plane slice is associated with one control plane slice. The authors evaluate three scenarios of their solution; same priority slices, ascending order priority slices and descending order priority slices (referring to PQ). Packets with low priority in the second and third scenarios may suffer from the starvation problem.

Table 4.1 Related Work.

ref	**QoS**	**QoE**	**Applications/Scope**
Benacer *et al.* (2018)	The order of inserting packets	None	Wireless networks
Shakir & Rajesh (2017)	Delay, service time and packet size	None	LTE networks
Anand & de Veciana (2017)	None	Mean flow delay	Wireless networks
Zheng *et al.* (2017)	The global throughput	Delay	Wireless networks
Hsieh & Hou (2018)	None	The duration of video playback interruption	Video-on-demand applications in Wireless network
Bakhshi & Ghita (2016)	Bandwidth	User-defined profiles	Multimedia and video streaming applications
Fan & Zhao (2018)	the average end-to-end delay	The frame buffer level at the destination nodes	Video Streaming
Yang *et al.* (2018)	Packet inspection	None	Video Streaming
Abuteir *et al.* (2016)	Real-time bandwidth	None	Video Streaming
Zeng *et al.* (2018)	None	Energy consumption	Vehicular networks
Butt *et al.* (2018)	Energy consumption	Loss tolerance	Loss tolerant App. in 5G
Chaabnia & Meddeb (2018)	None	Bandwidth allocation	Home network
Zeng *et al.* (2018)	Current active application/device	None	Home network

In general, most of the existing scheduling solutions rely on static metrics in the priority assignment task. They are either based on user-defined profiles, current active applications or class of service. Even though there are solutions that assign priorities dynamically (based on real-time bandwidth allocation or source-destination distance), they consider a specific type of home application (multimedia and video streaming applications) or only a particular optimization goal. They either focus on improving QoS from the perspective of ISP (optimize bandwidth utilization based on traffic loads to meet ToS priorities) or improving QoE from the perspective of the home user (optimize delay based on the distance between the source and destination nodes).

Specific queuing metrics, which need to be determined in smart home network, like traffic application criticality (or type of service) and the maximum required delay along with heterogeneous distributions queuing adaptability, has never been taken into account. These factors are very important in the context of the home network to fill the gap between QoS and QoE for any home application in an automated way. Our approach mitigates these limitations by considering these important key factors to deploy a new scheduling scheme specific to the smart-home network context. More specifically:

- Proposing a new deterministic queuing model for multi-sourced traffic generated with different distributions using a new composite QoS-level metric based on both criticality-based priority and delay-based priority to avoid local network congestion by optimizing the number of packets that meet their allowed delay while preserving their degree of criticality.

4.4 System Description

Fig. 4.1 depicts a typical smart home network. Each home network includes many different multimedia devices (i.e., tablets, smart-phones, connected TVs, etc.) and objects (i.e., sensors, electronics, appliances, etc.). Sensors are devices used to detect the location of people and objects or to collect data or states (i.e., temperature, energy consumption, open windows/doors, movement, broken glass). Electronic devices include phones, televisions, and laptops. Electrical devices refer to toasters, kettles, light bulbs, etc. Appliances refer to washing machines, refrigerators, etc.

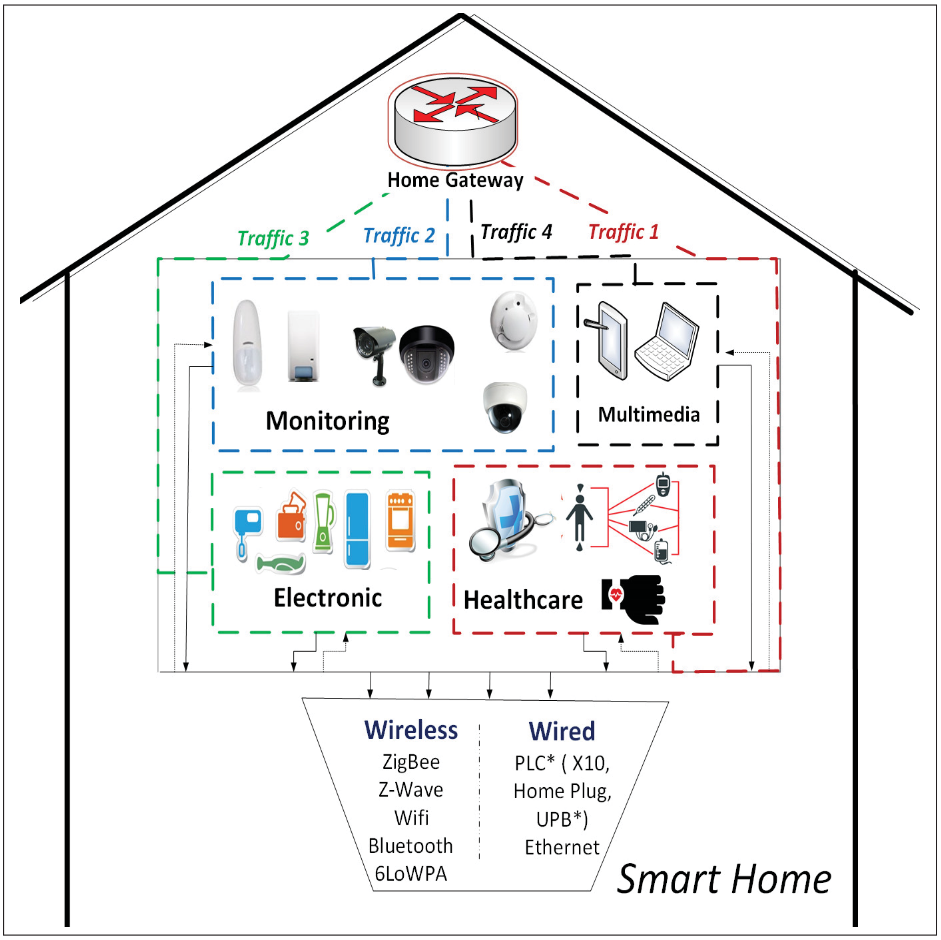


Figure 4.1 Smart Home Network.

Such a network offers services to a wide range of application like monitoring, health assistance, safety and energy efficiency, producing traffic with different Quality of Service (QoS) levels Simon & Kavitha (2017a); Curado *et al.* (2019); Gomez *et al.* (2019)(marked by different colors in Fig. 4.1) and managed by the smart home gateway.

Fig. 4.2 illustrates an example of the smart home gateway. Home gateway contains three modulesNowook *et al.* (2018); Classifier, Scheduler, and Service. In this paper, we use two-level classifier which classifies the network packets firstly according to their maximum allowed

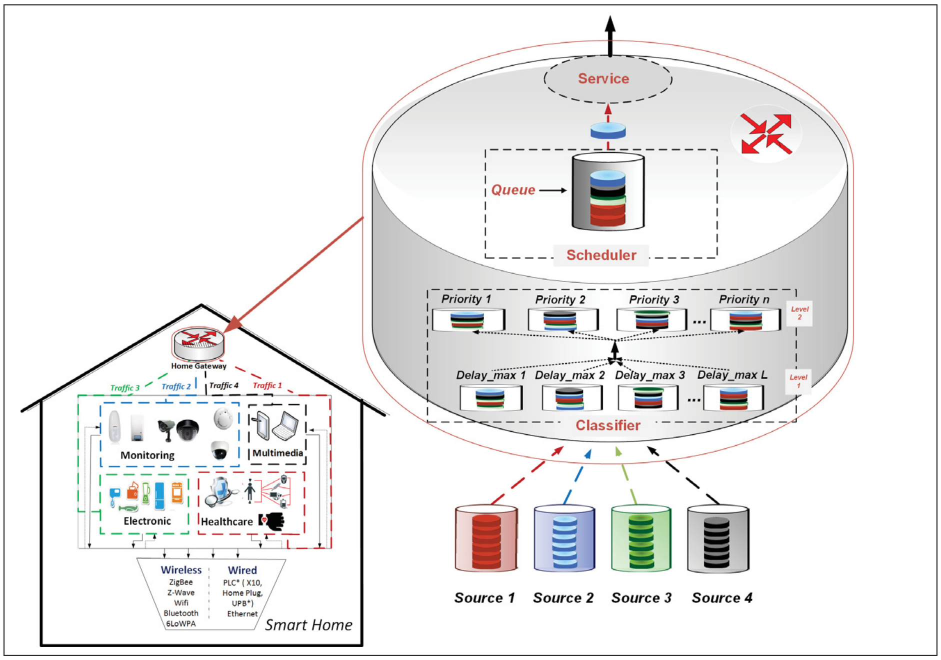


Figure 4.2   System Description.

delay and then, according their priorities. Scheduler contains the queue in which classified packets will be scheduled according to their arrived time and their two-level priorities. The number of priority classes n supported by the system depends on both the heterogeneity of constraints imposed by the traffic data and the maximum available bandwidth in the system. A small value of n may increase the available bandwidth while fulfilling fewer constraints with a partial QoS hierarchy. However, a high value of n may increase bandwidth utilization while satisfying QoS requirements for a large number of data type. Hence, by knowing the different types of traffic in smart home network and the bandwidth capacity of the home gateway, the number of priorities classes n can be fixed. Service module contains c parallel servers. We assume that the main queue of the system has an unlimited size (storage area) as long as the service module can process up to c packets per service time using its parallel servers.

4.4.1 Implementation model

Smart home network enables multiple smart objects to operate in one home gateway. Each network flow is assigned a priority group to prioritize their traffic by QoS packet marking using ToS (or DS) bits in the IP headerTietsch *et al.* (2019). On the other hand, each application is assigned a maximum allowed delay D_{max} that has to be met by their packets. Home gateway schedules network traffics firstly using w_{max} metric (see section 4.5.2) calculated based on their maximum delay D_{max} and then, using ToS field based on their assigned QoS priorities to provide both QoE and QoS in smart home network. In our proposed architecture, a simple modification on the IP protocol stack will be made by encapsulating a new field in the IP header that reflects the maximum allowed delay D_{max} for each packet besides ToS field.

The problem we address in this paper is to provide optimal scheduling for packets generated from different sources and with varying distributions with respect to their delay budget and their degree of criticality.

4.5 QOS-aware Scheduling Problem

Our problem is optimizing QoS scheduling for smart home network traffic. It consists of finding a way to schedule multi-sourced packets, that ensures their maximum tolerated delay and preserves their degree of criticality. The contribution of this paper is improving previous work by introducing a dynamic QoS level pair for multi-sourced traffic with different arrival rate, that considers the criticality of the application all along the maximum number of packets that can be processed before processing the packet based on its maximum tolerated delay.

4.5.1 Modeling and characterizing the input traffic and the service

Incoming traffic can follow different distributions depending on their data type as well as the type of their generation process (or source Si) as described in Fig. 4.3:

4.5.1.0.1 Periodic sensing objects (S_1)

These objects periodically detect and send to a central server (usually on the cloud) the states of monitored devices for each period T (i.e., connected thermostats, network sensors, medical sensors, etc.). A packet should be sent by sensors every period T and sent out by the gateway before 2T (the time when the following packet arrives). This type of source generates discrete traffic, with each period T (synchronous) and with a constant, determined distribution (D).

4.5.1.0.2 Event-triggered sensing objects (S_2)

These objects generate traffic by triggering some events (for example, door/window sensors, motion detectors, etc.) to indicate the status of the monitored object or person. Sensing data are delay-sensitive tasks that must be processed quickly to prevent serious property damage or injury since a small fire can rapidly turn fatal and we not always have enough time for safe evacuation. We define $D^{q_i}_{max}$ the maximum tolerated delay for QoS-level q_i traffic. The generation of this traffic is generally rare and does not depend on any other traffic (decorrelated). The arrival of this type of traffic (average arrival number λ_2)) can, therefore, be modeled according to a distribution of the Poisson process with an exponential inter-arrival rate (M).

4.5.1.0.3 Streaming objects (S_3)

These objects generate a continuous data stream (by tablets, connected televisions, surveillance cameras, etc.). These data do not always require QoS, however, for delay-sensitive applications like VOIP and video streaming (security camera or films), data should not be delayed to provide QoE (Quality of Experience) or security to the end user. Thus, the maximum tolerated delay for QoS-level q_i traffic generated from these type of objects is $D^{q_i}_{max}$. For video streaming applications, the maximum tolerated delay may increase as the frame rate decreases. Thus, the value of $D^{q_i}_{max}$ depends on the application requirements. For example, in video surveillance systems 7.5 frames per second (fps) are enough to capture and pause specific frames without noticing loss with the human eye Haldas (2018); Li *et al.* (2018). However, next-generation video devices like ultra-high definition TV (UHD), in which motion are often present, require higher frame rate with a minimum of 60 fps Jeong *et al.* (2017). Thus, the minimum required frame rate depends on the contents of the video. The higher the frames, the smoother the video will be. The generated data may reach peaks during periods of heavy use or may be negligible (like traffic from surveillance cameras or during the rest of the day). We have modeled this type of traffic with a binary Markov-Modulated Poisson Process (MMPP):

- State 0: incoming traffic follows a Poisson process with a very high average number of arrivals λ_3 ($\lambda_3 \gg \lambda_2$). This traffic corresponds to the flows generated during peak periods of use.
- State 1: incoming traffic follows a Poisson process with a low average number of arrivals λ_{31} ($\lambda_{31} \ll \lambda_3$). This traffic corresponds to the negligible flows generated during the rest of the day or by surveillance cameras.

The packet rate λ_2 generated by the source S_2 and the packet rate λ_{31} of the state 1 of the source S_3 are generally similar, and they can, therefore, be modeled by the same distribution with the same arrival rate λ_2. We can, therefore, consider that the average arrival rate $\lambda_2 = \lambda_{31}$ is fixed according to the utilization rate (the behavior of the inhabitants).

The arrival flow of our system therefore follows two different distributions; a predetermined distribution with an arrival rate λ_1 and a binary Markov distribution with an arrival rate ($\overline{\lambda_2}$). If we consider $Pr(s = i)$ the probability that an arrival packet is in state i (with $i \in \{0, 1\}$) then we have:

$$\overline{\lambda_2} = Pr(s=0)\lambda_2 + Pr(s=1)\lambda_3 \tag{4.1}$$

$$Pr(s=0) = \frac{r_1}{(r_0 + r_1)} \tag{4.2}$$

$$Pr(s=1) = \frac{r_0}{(r_0 + r_1)} \tag{4.3}$$

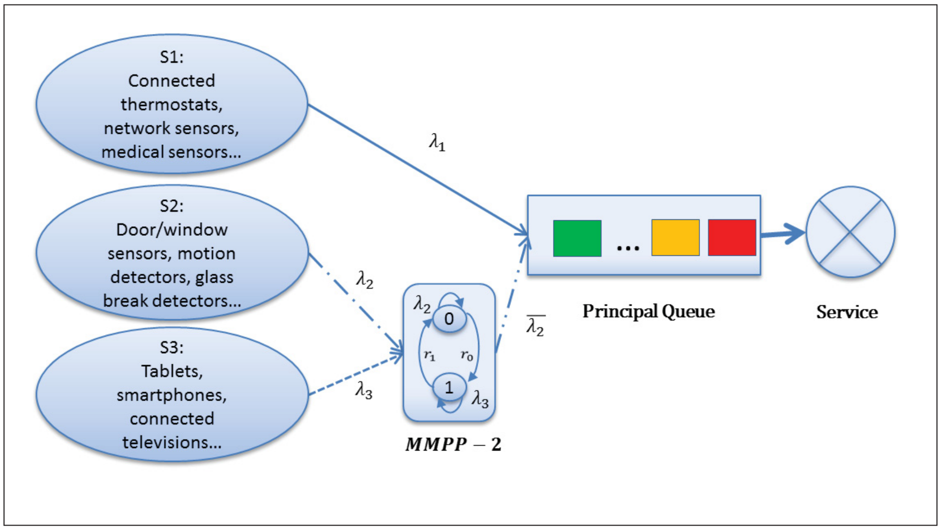


Figure 4.3 Modeling the input traffic.

with r_0 and r_1 are respectively the average lengths of stay in the state 0 and state 1 and therefore the arrival rate will be

$$\overline{\lambda_2} = \frac{\lambda_2 * r_1 + \lambda_3 * r_0}{(r_0 + r_1)} \tag{4.4}$$

We have a single domestic gateway with c servers. A server can process any packet with a size up to the Maximum Transmission Unit (MTU). We assume that all packets are MTU-sized packets and the service follows a deterministic distribution with a rate $\frac{1}{s}$.

4.5.2 Modeling QoS requirements for smart home network devices

For each smart home network application, we define a QoS level based on two main QoS parameters; a priority level and a maximum required delay. Priority level depends on the degree of the application criticality. Exceeding delay for critical applications is fatal, however, for non-critical applications, it is better to meet the deadline, but it is no crucial. For example, the processing time of packets generated from a fire detector must not exceed their maximum required delay otherwise the fire will rapidly turn fatal, however, a high processing time of a packet from video streaming applications, that exceeds its required maximum delay, will deteriorate the service without causing a real disaster. In our proposed architecture, three primary sources of traffic are considered (as described in section 4.5.1 and as shown in Fig. 4.3); type 1 sensor S_1, type 2 sensors S_2 and multimedia devices S_3, along with only one home gateway. Each source can generate different QoS-levels of network traffic at different time slots, and a maximum of c packets can be processed at each service time s using c parallel servers (each server can serve up to one packet in s time slots). The service time has a general distribution function. Our system is modeled as $D/G/c$ for traffic generated from source of type S_1 (since the interarrival time of data generated from periodic sensing objects S_1 is equal to a constant period of time and then, deterministic (4.5.1.0.1)) and $MMPP-2/G/c$ for traffic from sources of type S_2 and S_3 (since data generated from S_2 and S_3 are modeled with a binary Markov-Modulated Poisson Process (4.5.1.0.3)). The service can serve:

- Up to c packets in s time slots,
- Up to $\frac{c}{s}$ packets in one time slot,
- Up to $\frac{c * D_{max}(P_i)}{s}$ packets during the maximum required delay $D_{max}(P_i)$ of a packet P_i.

Thus, for each packet P_i we define a maximum window size $w_{max}^{P_i}$ as the maximum number of packets that can be processed by the system's service during its required delay $D_{max}(P_i)$ as follows:

$$w_{max}^{P_i} = \frac{c * D_{max}(P_i)}{s} \tag{4.5}$$

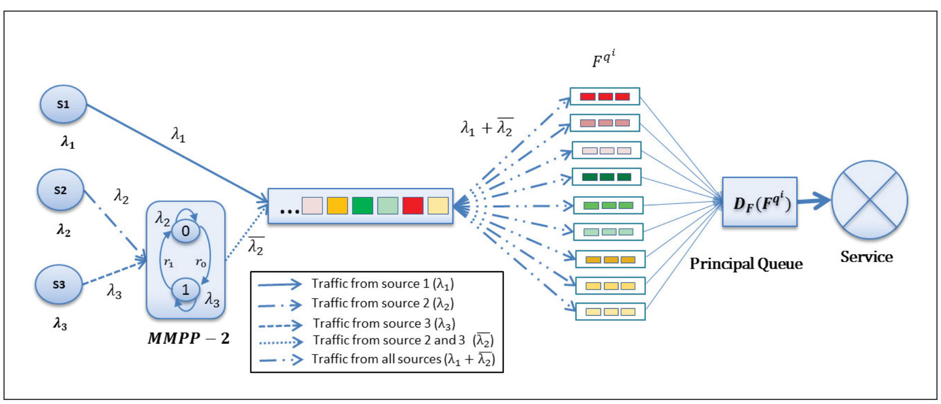


Figure 4.4 Composite QoS-level scheduling model.

We define the QoS-level pair q^{P_i}, for each network packet P_i as follows:

$$q^{P_i} = (p^{P_i}, w_{max}^{P_i}) \tag{4.6}$$

With p^{P_i} is the priority level of the P_i's application type.

As described in Fig. 4.4, we set a queue F^{q^i} for each QoS-level pair q^i and a scheduling discipline $D_F(F^{q^i})$ for composite QoS level packets from different F^{q^i} queues that we will determine later. We define a delay function for each packet $P^{(q,g)}$ generated from source S_i and having the QoS-level pair q as follow:

$$D_T(P^{(q,S_i)}) = \alpha_T(P^{(q,S_i)}) + s \tag{4.7}$$

With $\alpha_T(P^{(q,S_i)})$ is the waiting time of the packet $P^{(q,S_i)}$ before being served and s is the service time. All used parameters and functions are listed in Table.4.2.

Table 4.2 Notations.

Notations	**Definitions**
$S = \{S_i, i = 1, 2, \ldots\}$	Set of source of traffic in smart home
$F = \{F_i, i = 1, 2, \ldots\}$	Set of queues in the system
$Q = q^i$	Set of QoS-level pair q^i
$q^{(P_i)} = (p^{(P_i)}, w_{max}^{(P_i)})$	QoS-level pair of network packet P_i
$p^{(P_i)}$	Priority level of P_i's application type
$w_{max}^{(P_i)}$	Maximum number of packets that can be processed by the system's service before processing P_i
$D_{max}(P_i)$	Maximum required delay of P_i
$P = \{P_i^{(q,S_k)}\}$	Set of flows of QoS-level pair q and generated by source S_k
$P_i^{(q,S_k)} = \{P_{ij}^{(q,S_k)}\}$, $P_{ij}^{(q,S_k)}$	Flow i (of QoS-level pair q and from source S_k) and packet j of flow i
$D_F(F^{(q^i)})$	Scheduling discipline for composite QoS level queues
$\alpha_T(P_{ij}^{(q,S_k)})$	Waiting time function of packet $P_{ij}^{(q,S_k)}$ in the system
$D_T(P_{ij}^{(qS_k)})$	Delay function of packet $P_{ij}^{(q,S_k)}$ in the system

The smart home network is a heterogeneous infrastructure made of multiple electronic and electrical network devices like sensors, detectors, and laptops. These data sources generate a wide range of traffic with different distributions and various QoS and QoE requirements. A key challenge of this problem is to find a reasonable way to schedule multi-sourced packets from a composite class of service with respect to their QoS and QoE requirements. Thus, to meet the delay constraint, the delay of a packet $P_{ij}^{(q,S)}$ must be lower than the delay budget D_{max}^{q} required by the pair of class of service q:

$$D_T(P_{ij}^{(q,S)}) \leq D_{max}^{q} \tag{4.8}$$

The QoS-aware scheduling problem consists of finding an optimal way to schedule packets from multi-sourced traffic with dynamic QoS-level pair that ensures the maximum tolerated delay and preserves their degree of criticality. We formulate the QoS-aware scheduling problem by the following objective function:

$$(D_F(F^{q^i}))^* = argmin_{D_T(P_{ij}^{(q,g)})} \begin{cases} P_{ij}^{(q,g)} \in P \\ D_T(P_{ij}^{(q,g)}) \leq D_{max}^{q} \end{cases} \tag{4.9}$$

4.6 QP-SH: Queuing model for QoS-level Pair traffic in smart home network

To solve the queuing problem of smart home traffic that have a composite class of service $q^i = (p^i, w_{max}^i)$ and generated with different distributions, we propose a QP scheduling model as described in Fig. 4.5. The QP model dedicates a QoS-level pair $q^i = (p^i, w_{max}^i)$ for each packet generated from the different source of traffic. All packets with the same w_{max} will be merged to a single queue with the same w_{max} until reaching the main queue of the system. Then, packets in the same w_{max} queue will be scheduling according to their priority level p to ensure that each packet is processed according to its QoS-level pair whatever its source. In our proposed architecture, three main traffic sources are considered, as described in section 4.5.1 and as shown in Fig. 4.4; type 1 sensors (S_1), type 2 sensors (S_2) and multimedia devices (S_3).

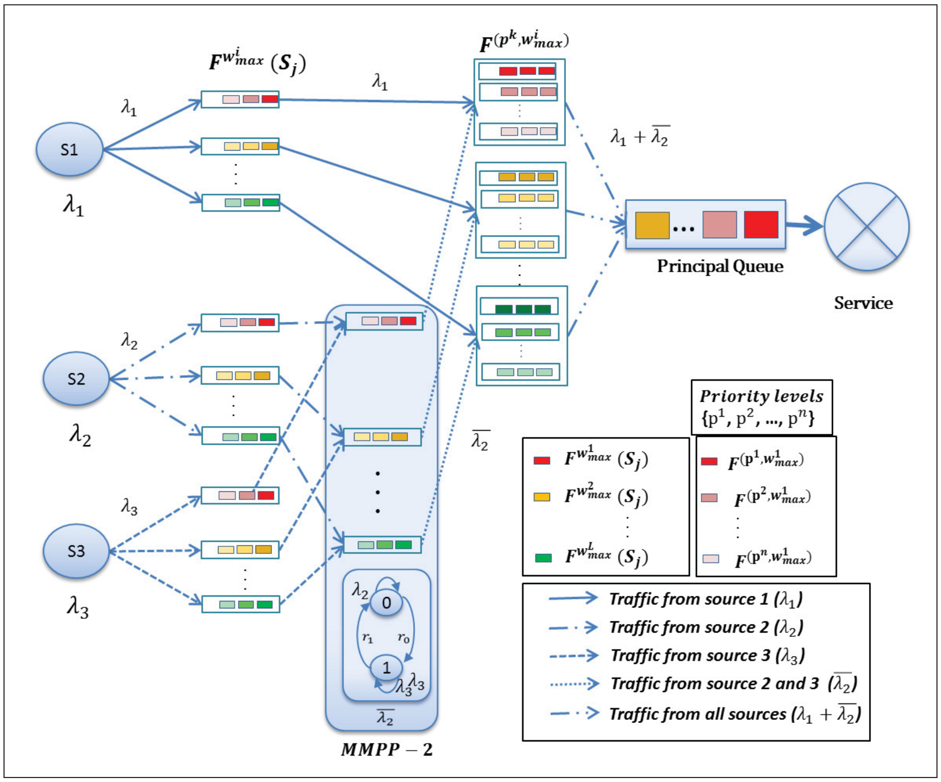


Figure 4.5 QP scheduling model.

Each source S_i has a set $F^W(S_j)$ of L queues for each w^i_{max} traffic generated from it with the rate $\lambda_j, F^W(S_j) = F^{(w_{max})}(S_j), w_{max} \in W \subset F$ with W is the set of w_{max}.

Algorithm 4.1 QP-SH: Queuing model for QoS-level Pair traffic in smart home network

Input: P, F
init P, F;
$k = c$ /* number of servers */
while $F^{w^*_{max}} = min_{w^i_{max}}(F^{w^i_{max}})$ *non empty and* $k! = 0$ **do**
  while $F^{p^{l^*}, w^*_{max}} = min_l(F^{p^l, w^*_{max}}), l \in [1, n]$ *non empty and* $k! = 0$ **do**
    pull(FIFO($F^{p^{l^*}, w^*_{max}}$));
    $k = k - 1$;
  end
  update(F, k);
end

Traffic from S_2 and S_3 are then modeled by a binary MMPP while keeping their priorities queues. All same w_{max} queues are merged to a single queue with the arrival rate ($\overline{\lambda_2}$). Then, all the same w_{max} queues from MMPP and S_1 are merged again to a single queue and sending to the principal queue with the arrival rate $\lambda_1 + \overline{\lambda_2}$ and $F^q = F^{(p,w)}, w \in W, p \in Q \in F^W \subset F$.

Algorithm 4.2 Init function

Input: P, F $//F = \{F^{w^i_{max}}, i \in L\}$;
$//F^{w^i_{max}} = \{F^{(p^k, w^i_{max})}(S_j), 0 \leq k \leq n, S_j \in S\}$;
$//P = \{P^{(q,S_k)}_{ij}\}$;
while *arriving packets at time slot* $t = P^t$ **do**
    for *each* $P^{(q,S_k)}_{ij} in P^t$ **do**
        push($P^{((p^k, w^i_{max}), S_k)}, F^{w^i_{max}}(S_k)$);
    end
    $F = \cup_{i \in L} F^{w^i_{max}}$;
end
for *each* $P^{(p^k, w^i_{max})}_{ij} \in F^{w^i_{max}}$ **do**
    push ($P^{(p^k, w^i_{max})}_{ij}, F^{(p^k, w^i_{max})}$);
    $//F^{(p^k, w^i_{max})} = F^{q^{ij}}$;
end

The QP-SH scheduling discipline is illustrated in Algorithm 4.1. The algorithm first initializes its queue using *init* function (Algorithm 4.2). Each arriving packet $P^{((p^k, w^i_{max}), S_k)}_{ij}$ generated from source S_k, is mapped to the queue $F^{w^i_{max}}(S_k)$ dedicated to its source. Then, all $F^{w^i_{max}}(S_k)$ queues from different sources of traffic will be merged to a single $F^{w^i_{max}}$ queue, packet per packet, based on their arriving times. All $F^{w^i_{max}}$ queues form a set $F = F^{w^i_{max}}, i \in L$ of queues. Then, all packets in each $F^{w^i_{max}}$ queue are grouped by priority into n sub-queues $F^{(p^k, w^i_{max})}$. The system processes all $F^{w^i_{max}}$ queuing in an ascending order beginning from the group of queue with the lowest w^i_{max} (Algorithm 4.1). Packets within the samew^i_{max} group are scheduling according to their priorities; packets highest priority are served first.

After each service round, the value of w^i_{max} for all $i \in L$ is decremented by the number of served packets (up to c packets since we have c servers), as the number of packets that can be

Algorithm 4.3 Update function

```
1 Input: P, F for each F^{w^i_{max}} in F do
2     F^{w^i_{max}} = F^{w^i_{max} - k};
3 end
```

processed by the system's service before processing each packet $P_i j^{((p^k, w^i_{max}), S_k)}$ is decremented by the number of served packets (see Algorithm 4.3).

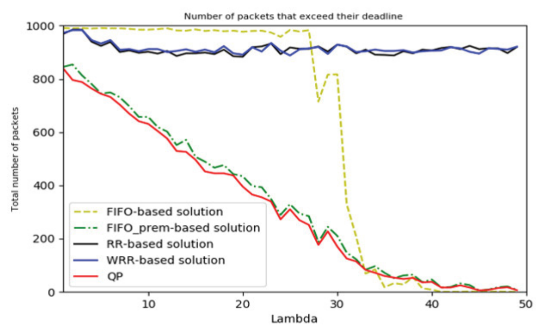
4.7 Performance Evaluation

To evaluate the performance of the proposed QP-SH algorithm, we build a simulation with up to 1000 network packets generated with different distributions and one server ($c = 1$). The D/G/1 model is simulated using traffic generated (from periodic sensing objects) each 5ms with a rate 1/5 packet/ms ($\lambda_1 = 1/5$). Incoming traffic from event-triggered sensing objects follow exponential distribution with a rate $\lambda_2 = 0.5 * \lambda_3$ since it is much lower than λ_3 (as described in section 4.5.1). This negligible traffic is generated during r_0 = 40% of the day.

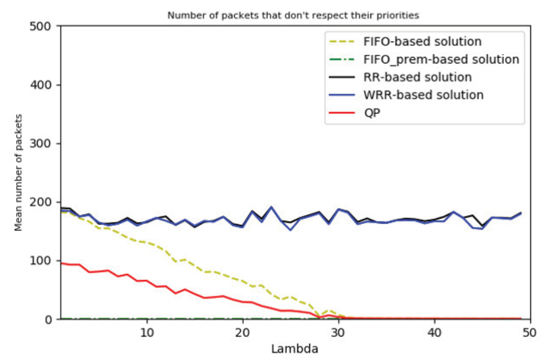
Table 4.3 Experimental Setup.

Parameter	**Value**
Number of packets	1000
D_{max}	uniform(200,250) (ms)
Priority	randint(0,10)
λ_1	1/5 (packet/ms)
λ_2	0.5 * λ_3 (packet/ms)
λ_3	1-50 (packet/ms)
Service time	30 ms (in scenario 1), 10-60 ms (in scenario 2)
r_0	40 (%)
r_1	20 (%)

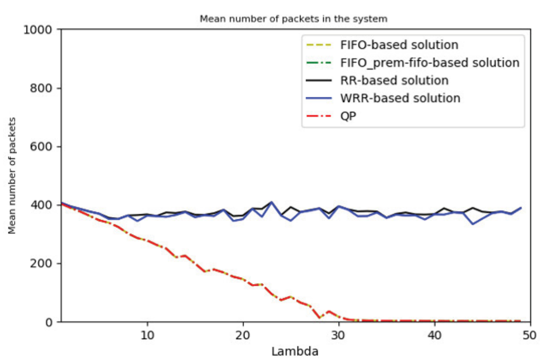
Incoming traffic from streaming objects follow exponential distribution with a rate λ_3 set from 1 to 50 packet/ms. This traffic is generated during periods of heavy use, during r_1 = 20% of the day. We calculate $\overline{\lambda_2}$ as defined in Eq.4.1. We randomly set the packet priority and the maximum delay. Regarding the service time, we consider two scenarios; in the first scenario, the service can serve a packet in 30 ms with a rate of 2 packet/s, and, in the second scenario, the service time varies from 10 ms to 60 ms. In both scenarios, we calculate the performance parameters of the global queue scheduling model based on the arrival rate $lambda = \overline{\lambda_2} + \lambda_1$ (where $\overline{\lambda_2} = \frac{r_0}{(r_0+r_1)}\lambda_2 + \frac{r_1}{(r_0+r_1)}\lambda_3$ as defined in Eq.4.1, Eq.4.2 and Eq.4.3). The different values of *lambda* are obtained by varying λ_3 from 1 to 50 and λ_2 in function of λ_3 (λ_2= 0.5 * λ_3). Table.4.3 describes our experimental setup.



a) Percentage of packets that exceed their maximum delays(%)



b) Percentage of packets that do not respect their priorities(%)



c) Mean number of packets in the system

Figure 4.6 QP-SH performances in function of the arrival rate *lambda* (the service time is fixed to 30 ms).

In Fig. 4.6, we consider the first scenario where the service time is fixed and we plot the curves of the number of packets that exceed their maximum delays (Fig.4.6(a)), the mean number of packets that do not respect their priorities (Fig.4.6(b)), and the mean number of packets in the system (Fig.4.6(c)) in function of the arrival rate *lambda*. These results are obtained using our QP-SH algorithm, the existing Round-Robin (RR) Shah *et al.* (2019) and Weighted RR (WRR) Sharma *et al.* (2018) based solutions and the existing First in First out (FIFO) and FIFO preemptive (FIFO-prem) based solutions Benacer *et al.* (2018). The mean number of packets that do not respect their priorities is obtained by comparing the QoS-level pair classification method (which is based on the priority provided by the two-level classifier; first using the maximum allowed delay and then, using QoS priorities) with that based on the QoS priority provided by the ToS field in the IP header.

We note that the curves obtained with QP-SH algorithm are under the curves obtained with the RR, WRR, FIFO and FIFO preemptive based solutions for the majority of criteria. We also note that the number of QP-SH based packets that violate their maximum delay and do not respect priority criterion decreases when we increase the arrival rate up to zero packets for arrival rates more than 40 packets/ms. However, varying the arrival rate has no impact on the performance of RR and WRR based solutions since they mainly focus on providing a level of fairness between packets from different QoS levels.

In Fig. 4.7, we consider the first scenario where the service time is fixed and we compare the performance of our algorithm QP-SH and the existing RR, WRR, FIFO, and FIFO-prem based solutions. The comparison is made based on the percentage of packets that exceed their maximum deadline, the percentage of packets that do not respect their priorities, and the mean number of packets in the system for different values of arrival rates. We note that the proposed QP-SH algorithm outperforms the existing solutions for the majority of criteria, with 15% higher for priority, 40% higher for the delay and 25% higher for the mean number of packets in the system. On the other hand, FIFO-prem based solution remains the optimal solution that guarantees priority criterion while increasing the delay since it is based only on priority. WRR and RR based solutions provide certain fairness between different QoS based packets while introducing the highest delay and the highest mean number of packets in the system.

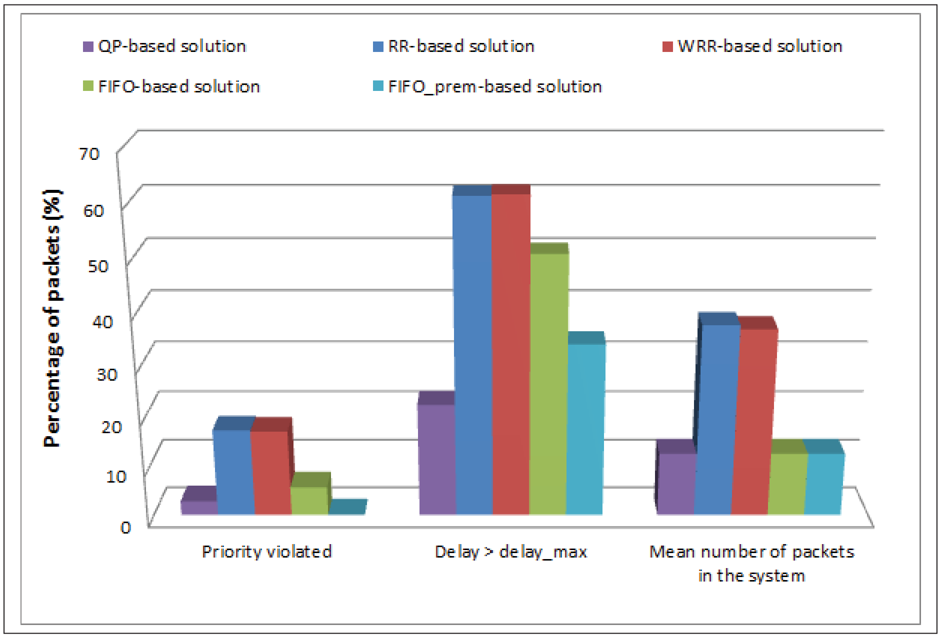
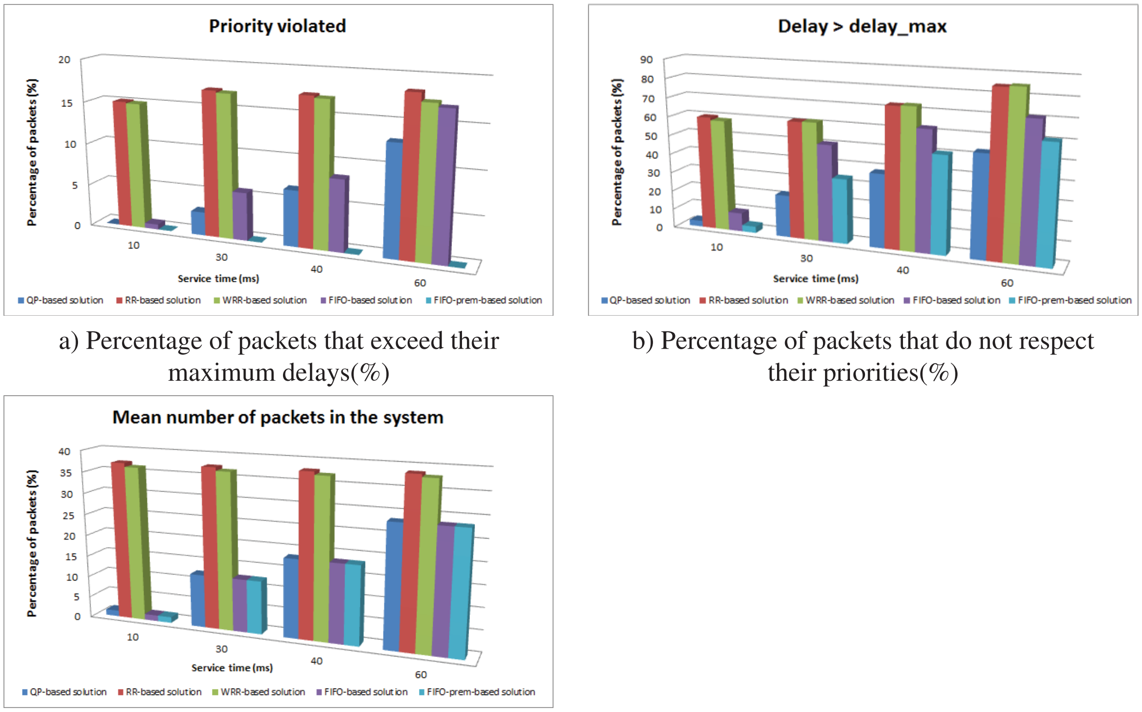


Figure 4.7 QP-SH performances compared to existing solutions (the service time is fixed to 30 ms).

We also study the performance of the proposed QP-SH and the existing based solutions (Fig. 4.8) regarding the impact of varying the service time on a) priority violation, b) deadline violation, and c) mean number of packets in the system. We note that when we increase the service time per packet, the performance of all solutions decreases and QP-SH maintains the lowest values except for FIFO-prem in priority criterion.

4.8 Conclusion

In this paper, we proposed a new dynamic queuing model for smart home network traffic generated by heterogeneous sources, to increase the number of packets that meet their deadline while preserving their degree of criticality. We tested our solution with 1000 network packets generated with different distributions. Then, we compared it to the existing based scheduling solutions for each criterion. Our experimental results demonstrated that the proposed algorithm outperforms the current solutions against almost all criteria.



a) Percentage of packets that exceed their maximum delays(%)

b) Percentage of packets that do not respect their priorities(%)

c) Mean number of packets in the system

Figure 4.8 QP-SH performances for different values of service time compared to existing solutions.

4.9 Acknowledgment

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CHAPTER 5

DYNAMIC QOS-AWARE SCHEDULING FOR CONCURRENT TRAFFIC IN SMART HOME

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5.1 Abstract

Smart home gateway has to process different types of network traffic generated from several devices in an optimal way to meet their QoS requirements. However, the fluctuation of network traffic distributions results in packets concurrency. Current QoS-aware scheduling methods in the smart home networks do not consider concurrent traffic in their scheduling solutions. This paper presents an analytic model for a QoS-aware scheduling optimization of concurrent smart home network traffic with mixed arrival distributions and using probabilistic queuing disciplines. We formulate a hybrid QoS-aware scheduling problem for concurrent traffics in smart home network, propose an innovative queuing design based on the auction economic model of game theory to provide a fair multiple access over different communication channels/ports, and design an applicable model to implement auction game on both sides; traffic sources and the home gateway, without changing the structure of the IEEE 802.11 standard. Our experiments show the proposed solution achieves an improvement of 14% of packets that meet their required delay and 57% of delay for different number of concurrent flows in the system.

Keywords: Concurrent traffic, quality of service, smart home, traffic scheduling optimization.

5.2 Introduction

As IoT (Internet of Things) and smart home applications flourish, the request for high-effective home networks with no congestion, less packet loss, and faster delay is significantly growing Qi *et al.* (2018). Smart home network connects different devices reacting with each other through heterogeneous wired and wireless physical accesses Khan & Zualkernan (2018). This class of devices includes sensors, home appliances, and multimedia devices and provides the home user with a large number of applications/services with different requirements in quality of service (QoS). Critical and delay-sensitive traffics, like medical, fire-detector and video streaming traffics, should be processed first, however medium and low-priority traffics, like network management and best-effort traffics, may wait in the queue for a while before being processed by the home gateway Kotani (2019). Prioritizing high-priority traffics may lead to network congestion when all the same QoS-level traffics access to the gateway service simultaneously and with insufficient network bandwidth which can create several consistency problems like extra long delay or even packet loss. Smart home networks are more likely to experience concurrency issues given the large number of smart devices which generates periodically (like sensors), randomly (like detectors which work with triggering) and continuous data (like streaming devices) through the network. The dynamic nature of today's home network caused by the fluctuation of network traffic distribution raises the problem of flow concurrency where multiple devices send simultaneously their data to the home gateway, enlarging system payload, dropping flows and increasing scheduling latency.

Recent advances in optical, wireless and cellular modulation technologies have been made from the perspective of increasing the number of concurrents users per media access Han *et al.* (2016). CSMA (carrier sense multiple access) widely used in existing systems, become less effective in delay for multi-channel/port concurrency issue. In addition, protocol design for multi-Channel Concurrency techniques Anand *et al.* (2015) does not consider the fairness between traffic flows from the same class of service which makes it unsuitable for delay-sensitive applications.

Designing an efficient fair scheduling solution for concurrent packets belonging to different ethernet ports or different channels remains a challenging task. Thus, scheduling with QoS in the context of the smart home network should consider flow concurrency for both different and same media access and fair scheduling between same QoS-level concurrent traffic to avoid packet loss, local network congestion and ensure fair queuing between network flows. This requires automated management of traffic loads within the home gateway by offering multiple concurrent access for the same channel/ethernet port.

In this paper, we propose an analytic model for optimizing concurrent packet scheduling in a smart home network with mixed arrival distributions and different QoS requirements. We also contribute an innovative probabilistic queuing model for smart home networks which provides a fair scheduling between concurrent traffic belonging to different media access using some unused bits in the MAC protocol stack without changing the structure of the IEEE 802.11 standard. The concurrent traffic schedule problem will then be modeled using an auction economic model of game theory and the solution is implemented on both traffic sources and the home gateway. The motivation behind the specific scheduling mechanism proposed for smart homes in this paper is two-fold: i) the specific traffic distribution in smart homes can be classified into three categories, as presented in Section 5.4, while in the general context like the Internet it is normal distribution which is hard to model; and ii) the game theoretical model can be easily implemented in the home gateway serving a limited number of flows in the home.
The rest of the paper is organized as follows. We will discuss related studies on QoS based scheduling in Section 5.3. In Section 5.4, we will describe the smart home traffic scheduling with concurrent flows. QoS scheduling problem is presented in Section 5.5. Section 5.6 describes the proposed queuing model for single QoS-level concurrent traffic in the smart home network (QC-SH). Performance results of our solution are provided in Section 5.7. Finally, we draw conclusions and present future work.

5.3 Related Work

Various scheduling strategies have been deployed in smart home context to improve energy efficiency Zhou *et al.* (2016); Chen *et al.* (2013), reduce power consumption Khan *et al.* (2019) and improve response time Leu *et al.* (2014). However, the multi-channel/port concurrency issue has not yet been considered in the smart home network.

The problem of providing concurrent accesses to a shared resource has been considered in several research areas; telecommunications Ding *et al.* (2018); Wang *et al.* (2018); Ma *et al.* (2019); Misra & Sarkar (2015); Wang *et al.* (2018); Jiang *et al.* (2019); Zhang *et al.* (2017), vehicular networks Zhang *et al.* (2019), computer systems Kim *et al.* (2019); Wang *et al.* (2019), etc.

Zhang *et al.* (2019) proposed a broadcast protocol for vehicular ad hoc networks (VANETs) which enables candidate forwarders in different transmission segments to concurrently transmit message packets. The authors used an accurate time synchronization mechanism to precisely calculate the packet forwarding time for each transmitter to satisfy concurrent transmissions requirements of orthogonal frequency division multiplexing (OFDM) signals in terms of the maximum temporal displacement. Despite the good performance provided by this solution in terms of the total broadcast delay, the large number of the concurrently transmitted messages can cause packet loss.

Many efforts have been done to improve spatial multitasking either through adding additional resources like multiple CPU cores or by maximizing thread-level parallelism Kim *et al.* (2019). Ding *et al.* (2018) contributed a new concurrent scheduling algorithm for wireless backhaul networks using contention graph. The spatial reuse of multiple flows is provided by the full-duplex aspect given the self-interference cancelation technology in mmWave networks besides its huge bandwidth. A new protocol for wireless sensor networks (WSN) is proposed in Ma *et al.* (2019) to enable concurrent transmission under interference. The protocol uses channel hopping to maintain communication with a continuous transmission when interference occurs. In Wang *et al.* (2018) a routing design for concurrent transmission is proposed. This design is based on the concurrent decomposition modular in the physical layer used by the collision avoidance techniques.

Game theory has been used in different research areas Misra & Sarkar (2015); Asadi & Mancuso (2017); Wang *et al.* (2018); Jiang *et al.* (2019); Wang *et al.* (2013). An evolutionary game-theoretic approach is considered in Liew *et al.* (2019) to solve the bottleneck problem of contention-based protocol in IEEE 802.11ah wireless standard. This game is used by the network access point to let a group of nodes contend for the channel access in its allocated Restricted Access Window (RAW) slot. The player payoff is modelled based on the node's throughput.

An inter-vehicle cross-layer MAC cooperative game model is proposed in Wang *et al.* (2018) to ensure the maximum allowed delay of message transmission in vehicular ad-hoc networks (VANETs). This approach uses Markov decision process (MDP) method to prove the existence a nash equilibrium.

A Reinforcement learning (RL) approach is considered in Bayat-Yeganeh *et al.* (2018) to learn the network conditions in terms of the number of nodes and their strategies. The proposed LR approach is used by a wireless node to find its optimal strategy in a multiple CSMA based medium access game that improves the system's throughput. The strategy of a wireless node is defined as its transmission probability.

A mean-field Bayesian game is proposed in Narasimha *et al.* (2019) to enable optimal transmission in ultra-dense multichannel wireless networks with distributed MAC. The optimal probing strategy is determined based on the Mean Field Nash Equilibrium that balances throughput and probing cost of each wireless device.

Another evolutionary game is proposed in Misra & Sarkar (2015) to reduce the average waiting time for local data processing units (LDPUs) in wireless body area network (WBAN). This approach uses the hawk-dove game to prioritize LDPUs based on the dissipated energy, the number of time slots the LDPU has been idle and the age and the gender of a person. A non-cooperative stochastic game is considered in Wang *et al.* (2018) to bypass malicious nodes in cognitive radio networks. Since a normal/malicious unlicensed user attempts to maximize/minimize the expected average of the cumulative link utility along its selected path (defined as the ratio of the link distance by the expected link delay), the authors calculated a Nash equilibrium to select the channel which maximizes this utility. A coalition game-theoretic approach is used in Asadi & Mancuso (2017) to solve the cluster formation problem in Device-to-Device (D2D) communications in 5G cellular networks. The game is used by the LTE base station to let the user join or leave a cluster based on its energy efficiency. Another coalition game is considered in Jiang *et al.* (2019) to enable full-duplex concurrent scheduling in millimeter wave wireless backhaul network. The game is used to find concurrently scheduled flows set with the maximum sum rate which maximizes the number of flows which satisfy their QoS requirements.

In general, prior work focus on parallel executions that require high-performance computing Zhang *et al.* (2019); Wang *et al.* (2019) and advanced hardware or protocol designs Wang *et al.* (2018); Ma *et al.* (2019) that require significant hardware or protocol modifications. However, a home gateway is a limited-resource system with limited bandwidth and computational capabilities compared to 5G and WSN networks Ding *et al.* (2018). This makes it difficult to deploy such complex, time and space-consuming approaches on a smart home gateway. Also, multiple access solutions provided by multiplexing systems Han *et al.* (2016) enable simultaneous transmissions over only a single communication channel. Multi-Channel Concurrency (CCM) Anand *et al.* (2015) in wireless systems allows concurrent multiple access over different channels from a single radio interface through using static or dynamic schedulers to control the switching frequency and the time allocation for each channel. These implementations cannot handle multi-channel/port concurrency issue.

Our approach mitigates these limitations by providing fair multiple access over different communication channels/ports smart-home network without generating a high overhead.

5.4 System Description

A smart home allows the home user to control or remotely manage a network of smart devices. These devices can be classified into three main classes according to the temporal distribution of their network data:

5.4.0.0.1 Periodic data

These data are generated periodically by sensors and are generally used for monitoring. The sensors detect and send at each period of time the states of monitored devices to a central server to create models for analysis ends. These sensing objects include; connected thermostats, network sensors, medical sensors, etc., and generate traffics with a constant, determined distribution.

5.4.0.0.2 Random data

These data are generated randomly by sensors and usually used for notifications. The sensors generate traffic by triggering some events to notify the user or the application server by the abnormal activity in order to prevent dangerous threats. For example, a glass break detector that can measure the window pressure could notify the homeowner via his phone when someone attempting to break in, or a fire detector that can predict fires based on other sensors (like smoke sensors and temperature sensors) could ask homeowners for evacuation. These sensing objects generate random time independent traffics and then based on the Poisson process distribution Grigoreva *et al.* (2017) with an exponential interarrival rate.

5.4.0.0.3 Continuous data

These data are generated continuously with a very high arrival rate during peak periods of use and lower arrival rate during the rest of the day or by surveillance cameras. These objects includes; tablets, smartphones, connected televisions, surveillance cameras, etc.

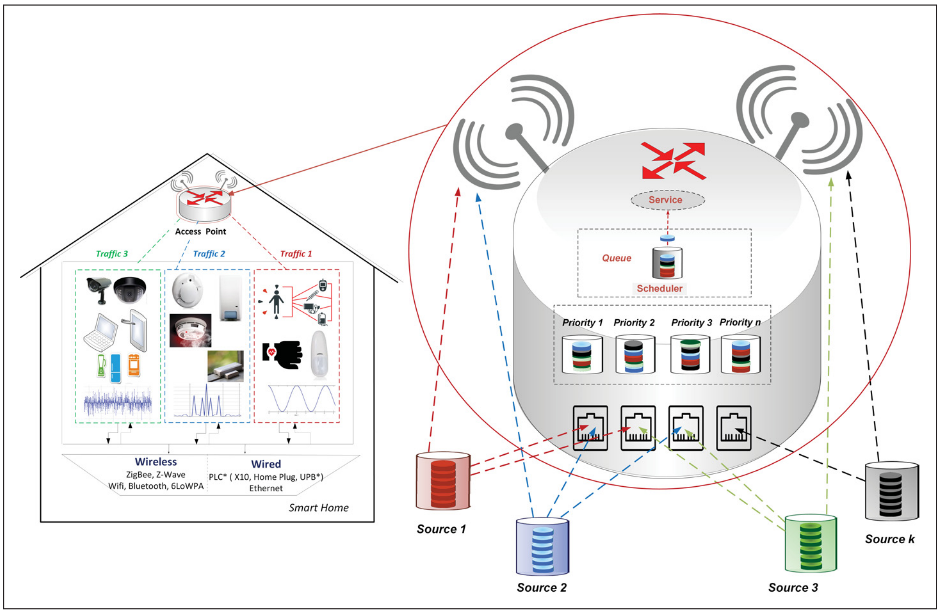


Figure 5.1 System Description.

In this paper, we extend the work done in Attia *et al.* (2019) to cover concurrent traffic issue in smart home network by proposing a new probabilistic queuing model that fairely schedules concurrent traffic using an auction game.

Fig. 5.1 depicts a typical smart home gateway. Home gateway has wireless and wired interfaces by which traffic will be redirected and routed from home network to the cloud. Each network device may communicate its generated data through Wi-Fi interface or Ethernet ports of the home gateway. These data will be classified according to their priorities (QoS level), scheduled according to their arrived time and QoS level, and then served by the service module. Given the wide range of services provided in the smart home network with a different requirement in QoS, the fluctuation of network traffic distributions and a large number of smart devices, each network channel or ethernet port may be parallelly shared by more than one active flow having the same QoS level. To deal with the network flow concurrency issue, we add a bidding module at the entry of the principal queue. This module uses an auction game which prioritizes packets according to their bid values as described in Section 5.6. In this paper, we assume that all the MAC protocols are based on IEEE 802.11.

5.4.1 Implementation model

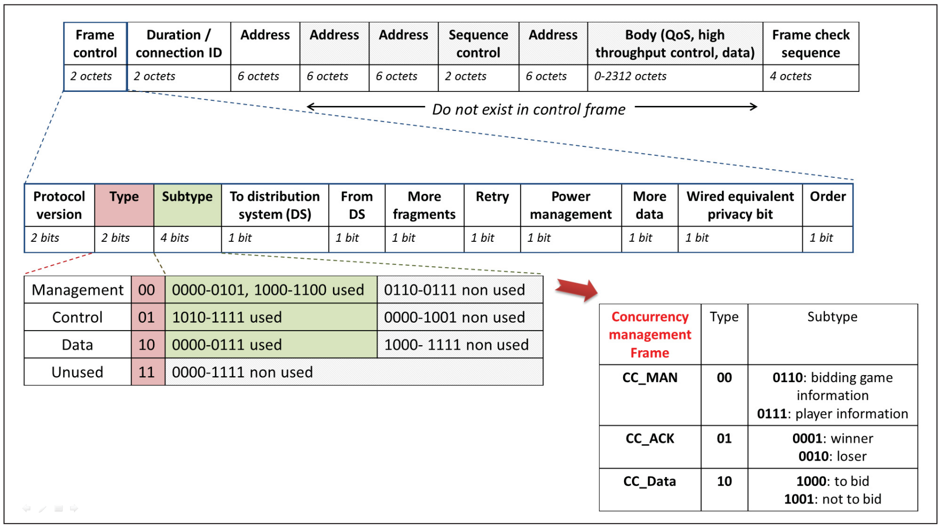


Figure 5.2 MAC frame structure of IEEE 802.11n.

Smart home gateway handles multiple different packets generated from diverse network objects. Each network packet is assigned a priority class through QoS packet marking using ToS (or DS) bits in the TCP/IP headerHou *et al.* (2019), and each class of traffic has a maximum allowed delay D_{max} that has to be met by their corresponding packets. On the other hand, a concurrent packet can have two states based on its bid value; it can be either a winner or a loser. In our proposed architecture, the state and the bidding value of each packet are implemented into the protocol stack without changing the structure of the IEEE 802.11 standard. Packet concurrency is managed by using some unexploited bits in the type and the subtype sub-fields of the frame control field in IEEE 802.11 frame (Fig. 5.2). While establishing communications inside the home network, each connected device send a *CC_MAN* frame (000111) to inform the home gateway of its maximum allowed delaying D_{max} and its initial valuation. Then, when there is concurrent traffic (when the gateway detects the presence of more than one packet with the same QoS level and arrival time, requesting access for the same channel/ethernet port), the home gateway broadcasts a *CC_MAN* frame (000110) to all devices in which belong the concurrent flows to inform that a new bidding game session is open and send them the total number of players (concurrent flows). For each player round, the gateway sends a *CC_ACK* to notify the player of its win (010001) or its loss (010010). Based on the received *CC_ACK*, the player updates its valuation and sends back a new bid value through a *CC_MAN* (000111). The packets from the winning bidder will be processed first by the gateway and packets from the loosing bidders remains at the principal buffer of the gateway (we assume that the main queue of the system has an unlimited size). Since bidding mechanism is implemented at the link layer, for both TCP and non TCP-based concurrent traffics, each data source may know whether it has won or not by checking its received link layer acknowledgments, and it updates its bidding value accordingly. MAC layer Management and control packets are lightweight packets compared to those of network layer which provide a communication with a negligible overhead Heydari & Yoo (2015). These packets are scheduled using preemptive FIFO queuing discipline unlike data packets which are served based on their QoS-levels and bidding values (in case of packet concurrency issue). All data packets are sent by the network devices using a *CC_Data* packet to inform the gateway that it wants to join (101000) or not (101001) a bidding game.

5.5 QOS-aware Scheduling Problem

Our problem is optimizing QoS scheduling for concurrent network flows generated from different communication channels/ports which have the same QoS-level and the same arrival time while respecting the maximum tolerated delay required by their QoS level (unlike the existing access control techniques Han *et al.* (2016) that consider flow concurrency for only the same media access). The solution can be implemented on traffic sources as well as on the home gateway.

5.5.1 System Model

Incoming traffic can follow different distributions depending on their data type as well as the type of their generation process. We have a single domestic gateway with c servers. A server can process any packet with a size up to the Maximum Transmission Unit (MTU). We assume that all packets are MTU-sized packets Nayak *et al.* (2016); Orosz *et al.* (2014) and the service follows a deterministic distribution Chen *et al.*; Metzger *et al.* (2019) with a rate $\frac{1}{s}$. Each data source can generate different QoS-levels of network traffic at different time slots, and a maximum of k packets can be processed at each service time using c servers. Our system is modeled as $G/D/c$. The service can serve:

- Up to c packets in s time slots,
- Up to $\frac{c}{s}$ packets in one time slot,
- Up to $\frac{c*D_{max}(P_i)}{s}$ packets during the maximum required delay $D_{max}(P_i)$ of a packet P_i.

Thus, for each packet P_i we define a maximum window size $w_{max}^{P_i}$ as the maximum number of packets that can be processed by the system's service during its required delay $D_{max}(P_i)$ as follows:

$$w_{max}^{P_i} = \frac{c*D_{max}(P_i)}{s} \tag{5.1}$$

5.5.2 Modeling concurrent traffic in smart home network

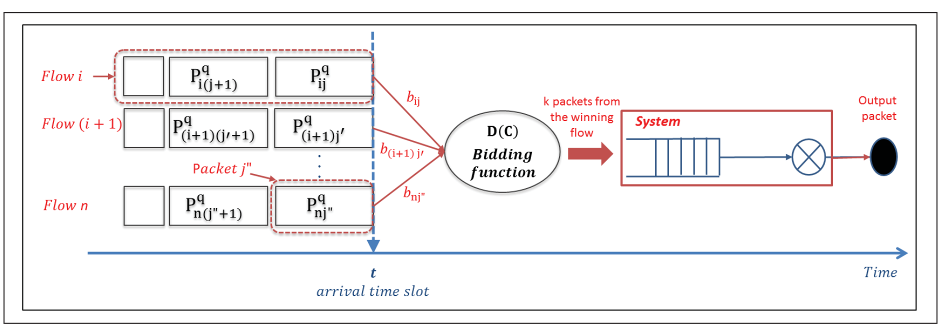


Figure 5.3 System model for concurrent traffics.

As described in Fig. 5.3, concurrent traffic $T = \{P_i^q, P_{i'}^q | i \neq i', i, i' \in R^+\}$ are flows that have the same QoS-level pair $q = (p, w_{max})$ and that each has at least one packet $P_{ij}^q \in P_i^q$ and $P_{i'j'}^q \in P_{i'}^q$ with the same arrival time slot t. We define the concurrent packets as $C = \{P_{ij}^q(t), P_{i'j'}^q(t') | P_{ij}^q \in P_i^q, P_{i'j'}^q \in P_{i'}^q, t = t'\}$ and the concurrent packet decision function as $D(C)$. Thus, the system will order the sequence of concurrent packet according to D(C). We also define $U(P_{ij}^{(q,g)})$ the decision utility function as the gain of resources required for sending a packet P_{ij}^{q} based on $D(C)$ function that we will determine later. The decision utility function is calculated as follows.

$$U(P_{ij}^{(q,g)}) = \sum_{q=1}^{|Q|} \sum_{c=1}^{|C|} D_T(P_c^{q,g}) - D_T^*(P_c^{q,g}) \tag{5.2}$$

where $D_T(P_c^{q,g})$ and $D_T^*(P_c^{q,g})$ are respectively the delay of processing the packet (P_c^q) before and after applying the $D(C)$ function and are defined as the sum of waiting time in the queue and service time. All used parameters and functions are listed in Table 5.1.

Table 5.1 Notations and Definitions

Notations	**Definitions**
$Q = q^i$	Set of QoS-level pair q^i
$D_{max}(P_i)$	Maximum required delay of P_i
$w_{max}^{P_i}$	Maximum number of packets that can be processed by the system's service during the maximum required delay of P_i
$P_i^q = \{P_{ij}^q\}$, P_{ij}^q	Flow i (of QoS-level q) and packet j of flow i
$T = \{P_i^q, P_i'^q\}$	Set of concurrent flows of QoS-level q
$C = \{P_{ij}^q(t), P_{i'j'}^q(t)\}$	Set of concurrent packets of the same QoS-level q
$D(C)$	Concurrent-packet decision function
$D_T(P_{ij}^{(qS_k)})$	Delay function of packet $P_{ij}^{(q,S_k)}$ in the system

The smart home network is a heterogeneous infrastructure made of multiple electronic and electrical network devices like sensors, detectors, and laptops. These data sources generate a wide range of traffic with different distributions and various QoS requirements. A key challenge of this problem is to find a reasonable way to schedule multi-sourced and concurrent packets with respect to their QoS requirements. Thus, to meet the delay constraint, the delay of a packet $P_{ij}^{(q,S)}$ must be lower than the delay budget D_{max}^q required by the class of service q:

$$D_T(P_{ij}^{(q,S)}) \leq D_{max}^q \tag{5.3}$$

The QoS-aware scheduling problem consists of finding an optimal way to schedule packets from multi-sourced and concurrent traffic while ensuring their maximum tolerated delay and maximizing the concurrent-packet utility function $U(P_{ij}^{(q,g)})$. We formulate the QoS-aware scheduling problem by the following objective function:

$$(D(C))^{*} = \begin{cases} arg_{max}(U(P_{ij}^{(q,g)})), P_{ij}^{(q,g)} \in P \\ D_T(P_{ij}^{(q,g)}) \leq D_{max}^{q} \end{cases} \tag{5.4}$$

5.6 QC-SH: Queuing Model for single QoS-level Concurrent traffic

The QC-SH, the innovative mechanism proposed in this paper, is inspired by the concept of auction used in game theory. We applied a bidding mechanism on concurrent packets to fairly schedule them with respect to their maximum tolerated delay required by their QoS level. Each source can place a bid based on the number of packets it wants to process. This bid is re-calculated at each bidding round using the previous bid result, and the maximum tolerated delay required by the source QoS level. The system model for concurrent traffics is described in Fig.5.3.

5.6.1 Game Description

QC-SH is based on a multi-player bidding mechanism. We define the concurrent packets C as the players and the aim is to be proceeded. There are $|C| = n$ players with valuations $v_1, \ldots, v_n$. In each bidding round, each player $P_{ij}^{q} \in C$ places a bid b_{ij}^{q}. The player with the maximum bid wins and will be processed by the system as well as its following k packets from$P_i^q \in T$ as described in Fig.5.3.

At each bidding round r, the system compares the bidding values of the concurents flows and sends $sent_{ij} * w_{max}^{q} = (v_{ij} - b_{ij}) * w_{max}^{q}$ packets from the winning flow P_{ij}^{q} using its bid value b_{ij}

and its valuation v_{ij} at each round r_i as follows:

$$sent_{ij}(r_i) = \begin{cases} v_{ij}(r_{i-1}) - b_{ij}(r_i) & \textbf{if } P^q_{ij} \textbf{ wins round } r_i \\ 0 & \textbf{if } P^q_{ij} \textbf{ looses round } r_i \end{cases} \tag{5.5}$$

For each concurrent flow $P^q_i \in T$, we set a maximum window size w^q_{max} (see Eq.5.6) as the maximum number of packets that can be processed by the system's service during its required delay $D_{max}(P^q_{ij})$. The initial valuation of a player P^q_{ij} corresponds to $v_{ij}(r_0) = \frac{w^q_{max}}{w^q_{max}} = 1$ and it is updated at each playing round as follows:

$$v_{ij}(r_i) = \begin{cases} v_{ij}(r_{i-1}) - sent_{ij}(r) & \textbf{if } P^q_{ij} \textbf{ wins round } r_i \\ v_{ij}(r_{i-1}) + sent_{ij}(r) & \textbf{if } P^q_{ij} \textbf{ looses round } r_i \end{cases} \tag{5.6}$$

If a packet P^q_{ij} wins a round, its valuation v_{ij} decreases by the number of sent packets by the system, but if it loses a round, its valuation increases to cover its loss from the previous round and to increase its winning probability. Thus, the probability of successful processing of packets of a source increases with its previous loss rate.

For each concurrent packet $P^q_{ij} \in C$, we define a window size w^q_{ij} as the number of sub packets P^q_{ij} to be processed by the system during the delay of $P^{(q,g)}_{ij}$ as follows:

$$w^q_{ij} = \frac{c * D(P^{(q,g)}_{ij})}{s} \tag{5.7}$$

Whether a player wins or looses, the system calculates its utility U^q_{ij} at each playing round r_i as follow:

$$U^q_{ij}(r_i) = Pr^{ij}_{win}(r_i) * \frac{sent_{ij}(r_i)}{w^q_{max}} = Pr^{ij}_{win}(r_i) * [v_{ij}(r_{i-1}) - b_{ij}(r_i)] \tag{5.8}$$

where $Pr^{ij}_{win}(r_i)$ is the winning probability of packet P^q_{ij} in round r_i

5.6.2 Game Model

As described before, the system sends $v_{ij} - b_{ij}$ packets from the winner flow. Thus, the system wants to maximize the bid value to achieve some fairness between concurrents traffic by sending a few packets from each flow to increase the probability of winning for other players. However, concurrent flows want to minimize their bid to send a maximum number of packets from its flow. Based on the tradeoff between the selected winner and the number of processed packets, we model our game as follows:

- **Type**: First price auction game. It allows the concurrent traffic to choose its strategy based on its window size.
- **Players**: a finite set N of concurrent traffics
- **The resource that the palyers play for**: The media access to transmit its packets over the acquired priorities.
- **Game coordinator**: The home gateway
- **Strategies**: S= set of actions = R^+
- **Initial valuation**: $v_{ij}(r_0) = \frac{w^q_{max}}{w^q_{max}} = 1$
- **Winner**: the player with the highest bid
- **Utility**: $U_{ij}(v,b) = 1(b_i \geq max_{j \neq i} b_j)(v_{ij} - b_{ij})$
- **Duration of the game**: $T = \varepsilon + k\delta$; with k is the total number of packets to be sent concurrently, δ is the duration of one packet (=MTU), ε is game computation, evaluation, and analyses times.

5.6.3 Nash Equilibrium

The valuations v_i of the concurrent flows are independent and identically distributed across the players and follow the uniform distribution on [0,1]. $b^*(v)$ is a symmetric Bayesian nash equilibrium (BNE) for each concurrent packet P^q_{ij} if $b^*(v_{ij})$ is its best response when all other players bid $b^*(v_{i'j'})$. The existence of a BNE in First price auction is proven by Lebrunen in Lebrun (1996). Let F and f be respectively the general cumulative distribution function (strictly increasing) and the probability density function. We assume that the symmetric BNE $b*$ is strictly increasing and differentiable.

The utility of the packet P_{ij}^{q} with valuation $v_{ij} \in [0,1]$ and bid $b(w) \in [0,1]$ is as follows:

$$\begin{aligned} U &= P_{win}[v - b(w)] \\ &= P(max_{j \neq i} b(j) \leq b(w))[v - b(w)] \\ &= [F(w)]^{n-1}[v - b(w)] \end{aligned} \tag{5.9}$$

with a derivation equal to :

$$\frac{\partial U}{\partial w} = (n-1)[F(w)]^{n-2} f(w)[v - b(w)] - b(w)'[F(w)]^{n-1} \tag{5.10}$$

The utility is maximized using the first order condition described in Eq.5.11:

$$\begin{aligned} &\frac{\partial U}{\partial w}_{|w=v} = 0 \\ &\leftrightarrow (n-1)[F(v)]^{n-2} f(v)[v - b(v)] - b(v)'[F(v)]^{n-1} = 0 \end{aligned} \tag{5.11}$$

Thus, $b^*(v) = \frac{v(n-1)}{n}$ is a symmetric Bayesian nash equilibrium for the game since it maximizes the utility given any valuation v.

$$\begin{aligned} &\int_0^x \frac{\partial U}{\partial w}_{|w=v} \mathrm{d}v = 0 \\ &\leftrightarrow [F(v)^{n-1} * v]_0^x - \int_0^x F(v)^{n-1} \mathrm{d}v - [F(v)^{n-1} * b^*(v)]_0^x = 0 \\ &\leftrightarrow v * F(v)^{n-1} - \frac{v^n}{n} - b^*(v) * F(v)^{n-1} = 0 \\ &\leftrightarrow v^n - \frac{v^n}{n} - b^*(v) * v^{n-1} = 0 \\ &\leftrightarrow b^*(v) = \frac{v^n - \frac{v^n}{n}}{v^{n-1}} \\ &\leftrightarrow b^*(v) = \frac{v(n-1)}{n} \end{aligned} \tag{5.12}$$

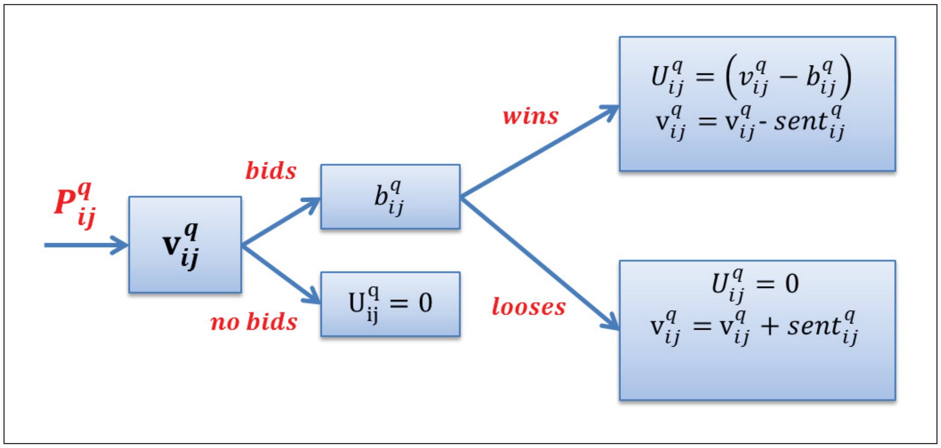


Figure 5.4 Game model for concurrent traffics.

The game model for concurrent packet flows is described in Fig.5.4. To further explain this model, we use a simple example of two concurrent flows $P^q_i, P^q_{i'} \in T$ from the same service class pair q, as presented in Fig.5.5 which illustrates the transitions of the bidding value, the valuation and the number of packets sent for each bidding round of both flows. In the example, we assume a gateway with one server, and a service time of 5 ms, the maximum delay required by the service class q is $D^q_{max} = 40$ ms and both flows have the same size $flow_{size} = 20$ packets and the same initial valuation $v_{ij} = v_{i'j'} = 1$ (of the first packet). Initially, the two flows have the same bidding value calculated as in Eq.5.12 (since they have the same initial valuation), thus the system chooses randomly the winner ,i.e., P^q_i for the first round. Then, each packet updates its valuation as in Eq.5, and in the second round, the system selects the packet with the highest bidding value as the winner. In this way, the entire flow $P^q_{i'}$ is treated in 8 rounds, and the entire flow P^q_i is treated in 7 rounds, so both flows require 8 rounds with a maximum delay of $D^q_{max}(8rounds) = 8 * D^q_{max} = 320$ ms. On the other hand, without our bidding mechanism both P^q_i and $P^q_{i'}$ flows are treated in $(2 * flow_{size})$ rounds=40 rounds (one packet per round since they are treated sequentially) and with a maximum delay of $D^q_{max}(40rounds) = 40 * D^q_{max} = 1600$ ms. In this example, our solution reduces 1600-320=1280

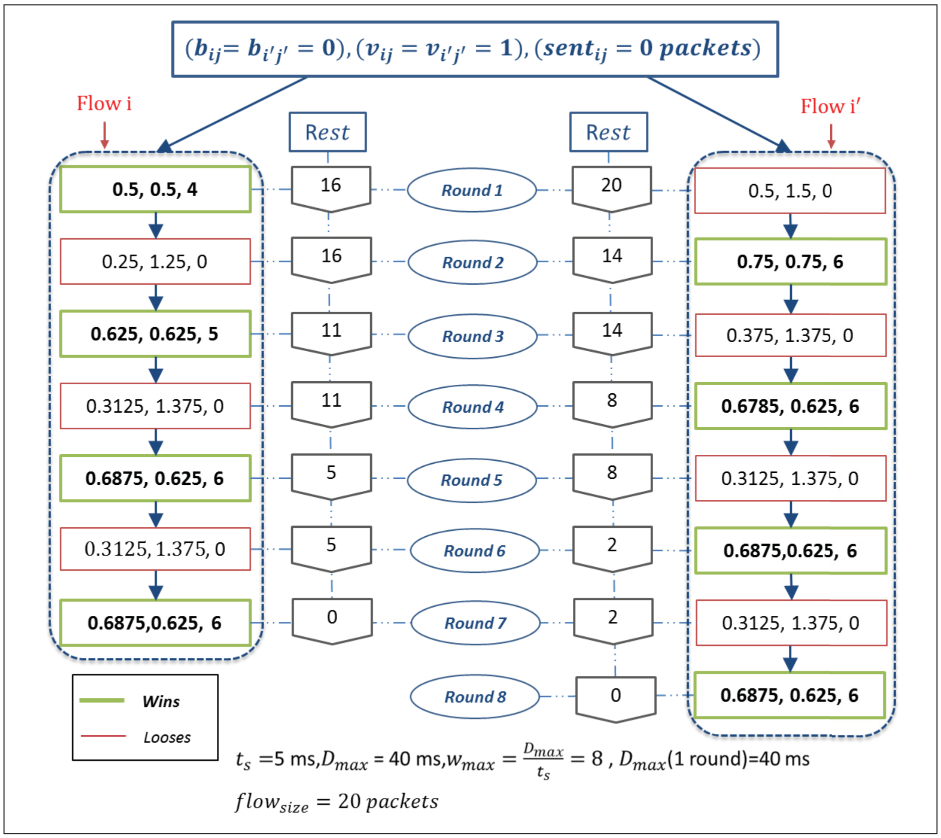


Figure 5.5 Example of processing of two concurrent flows.

ms in delay for processing two concurrent flows of 20 packets each. The QC-SH scheduling discipline is illustrated in Algorithm 5.1.

5.7 Performance Evaluation

5.7.1 Experimental Setup

To evaluate the performance of the proposed QC-SH algorithm, the experiment was carried out in a simulated network environment similar to the smart home network one. We build a simulation with up to 200 concurrent flows (since the short distance between two homes makes the home gateway able to serve more than one home at the same time) generated from different sources, each has $flow_{size} = 20$ network packets. The flows are processed using 4

Algorithm 5.1 QC-SH: Queuing Model for single QoS-level Concurrent traffic

```
Input: T, D^q_max, s, c /* s is the service time, c is the number of
    servers                                                        */
Output: Concurrent flows scheduled n = |T| /* the number of concurrent
    flows                                                          */
w^q_max = c*D_max / s ;
for each P^q_ij in T do
|   v_ij = 1 ;
end
while T non empty do
|   for each P^q_ij in T do
|   |   b^q_ij = v_ij(n-1) / n ;
|   end
|   Select P_w from T that has the highest bidding value b^q_ij /* select the
|       winner flow                                                */
|   sent_w ← v_w - b_w ;
|   v_w ← v_w - sent_w ;
|   Process sent_w * w_max^q packets from P_w ;
|   if P_w is empty then
|   |   /* all packets from flow P_w are processed                 */
|   |   T ← T - P_w ;
|   end
|   for each P^q_ij in T and P^q_ij ≠ P_w do
|   |   sent_ij ← 0 ;
|   |   v_ij ← v_ij + sent_w ;
|   end
end
```

servers and with a service time = 5 ms. The maximum delay required by the service class q of concurrent flows is $D^q_{max} = 40$ ms. We calculate the maximum number of packets w_{max} that can be processed by the system's service during the required delay D_{max} as defined in Eq.(5.1). Table. 5.2 describes our experimental setup.

We compare our QC-SH algorithm with recent mono-processing and multiprocessing scheduling approaches follow:

Table 5.2 Experimental Setup.

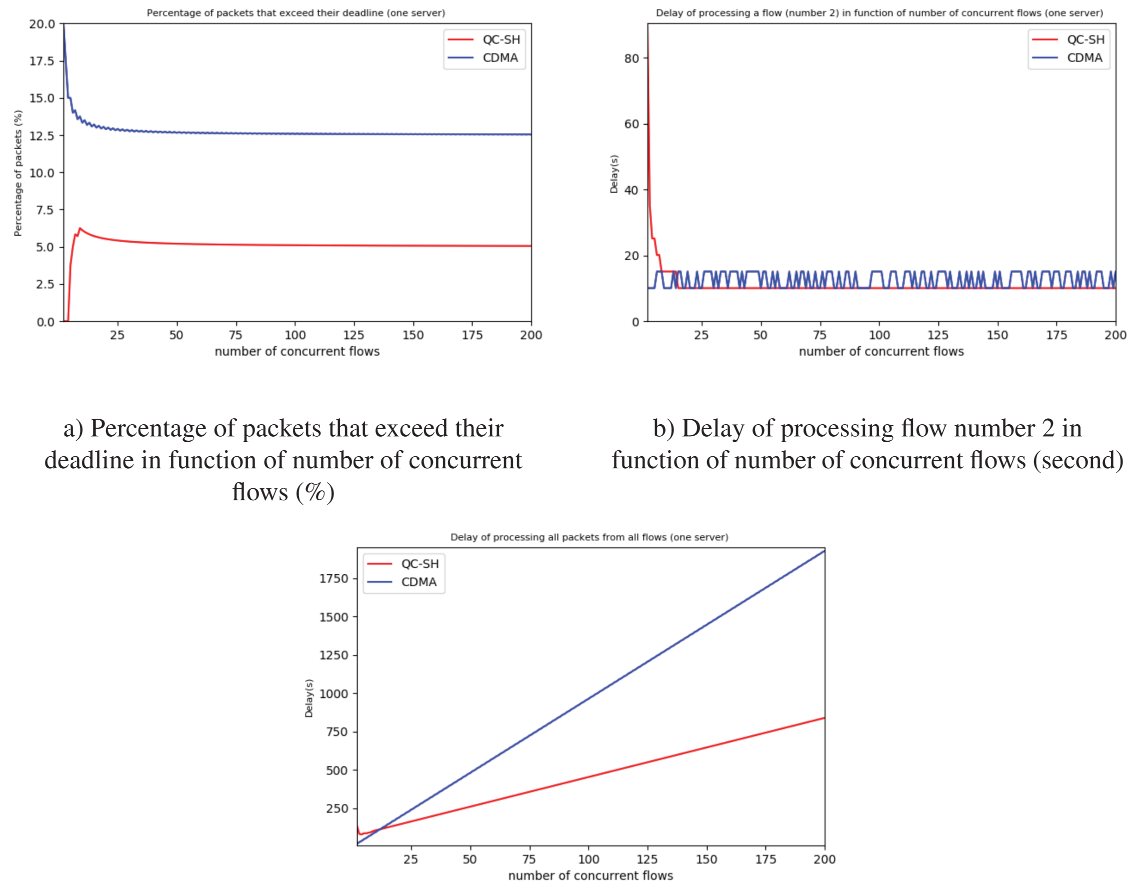
Parameter	Value
Number of concurrent flows	2-200
Number of packets	80-4000
Number of servers	1, 4
The maximum required delay	40 ms
Service time	5 ms

- Mono-processing approaches: Theses approaches consider a single server. They include TDMA solution Jiang *et al.* (2019)(it serially transmits packets) and concurrency-based scheduling solutions like CDMAHan *et al.* (2016), STDMAJiang *et al.* (2019), SFDJiang *et al.* (2019), and others Zhang *et al.* (2019); Han *et al.* (2016); Jiang *et al.* (2019). In our experimentation, we use *CDMA* approach as a candidate to refer to this group since all channels/ports concurrent approaches are based on the CDMA solution. CDMA allows multiple access over a single media access (channel/port). However, for concurrent traffic over multi-channels/ports CDMA performs as TDMA as it processes a single packet in each media access. With a focus on multi-channels/ports concurrency issue, we simulate the CDMA approach by serially transmit concurrent packets for each channel/port. We setup the CDMA approach using 1 server and 200 concurrent flows.
- Multiprocessing approaches: These approaches consider more than one server. They include concurrency-based scheduling solutions that allow spatial multitasking using multiple CPUs Ding *et al.* (2018). We refer to this group $Parallelism$ and we setup it using 4 servers and 200 concurrent flows.

The auction game algorithm proposed under concurrency issue is called QC-SH algorithm.

5.7.2 Experimental Results

Fig. 5.6 shows the performances of the proposed QC-SH algorithm in terms of the number of concurrent flows compared to the CDMA approach Han *et al.* (2016) using a single server. Three metrics are considered: a) the percentage of packets that exceed their deadline (Fig. 5.6(a)), b) the delay of processing a single flow (we test with the flow number 2 as it is



a) Percentage of packets that exceed their deadline in function of number of concurrent flows (%)

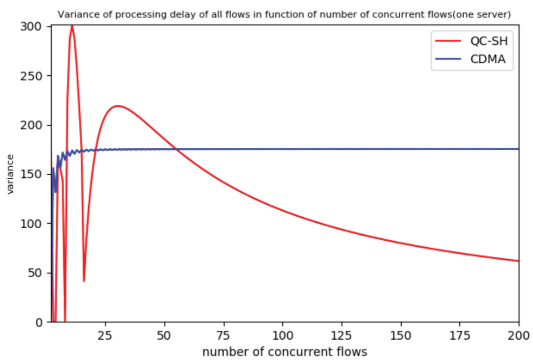
b) Delay of processing flow number 2 in function of number of concurrent flows (second)

c) Delay of processing each flow in function of number of concurrent flows (second)

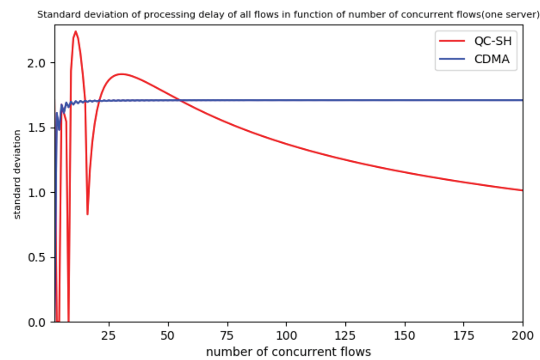
Figure 5.6 QC-SH performances in function of number of concurrent flows (one server).

always present for different number of concurrents flows; from 2 to 200) (Fig. 5.6(b)), and c) the delay of processing each flow (Fig. 5.6(c)). We can see our solution provides lower delay for processing all flows and a lower number of packets that exceed their deadline compared to CDMA. QC-SH provides a minimum of 94% of packets that respect their maximum delay compared to 80% with CDMA (an improvement of 14%). The processing delay of all flows with QC-SH is lower than that with CDMA (Fig. 5.6(c)). This can be explained by the fairness feature of our solution in order to provide a lower total processing delay for concurrent flows. As shown, QC-SH processes up to 200 concurrent flows in a maximum of 750s, with around

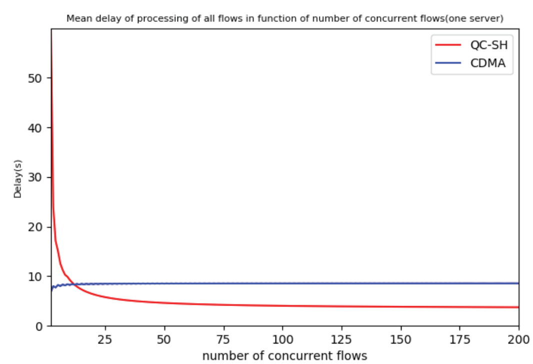
10s and 2 processing rounds per packet) compared to up to 1750s with CDMA, with around 18s and 4 processing rounds per packet (an improvement of 14%). Therefore, our approach performs better in heavy concurrent traffic condition which is the case of smart home network.



a) Variance of processing delay of all flows in function of number of concurrent flows (second)



b) Standar deviation of processing delay of all flows in function of number of concurrent flows (second)



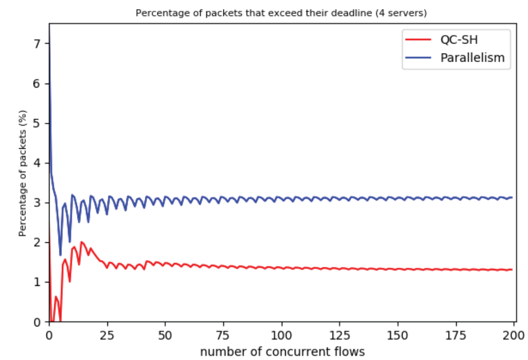
c) Mean delay of processing of all flows in function of number of concurrent flows (second)

Figure 5.7 Statistical performances for QC-SH in function of number of concurrent flows (one server).

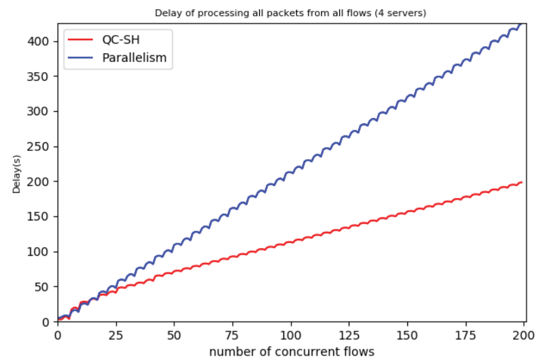
We also study the fairness of processing concurrent flows using the statistical parameters of the proposed QC-SH in terms of the number of concurrent flows and using a server (Fig. 5.7). We compare the statistical performances of the proposed QC-SH to the CDMA solution in terms of a) the variance (Fig. 5.7(a)), b) the standard deviation (Fig. 5.7(b)), and c) the mean delay of processing of all flows (Fig. 5.7(c)). When we increase the number of concurrent flows, both the variance and the standard deviation of the processing delay with QC-SH decrease while remaining under CDMA curves. When we increase the number of concurrent flows, the processing delay of all flows will be close to the average. We conclude that the fairness feature of our solution makes it less sensitive to the fluctuation of the number of concurrent traffics. Furthermore, QC-SH experiences a lower mean delay for any number of concurrent flows compared to the CDMA solution. We note that at the beginning of the experiment (with the lower number of concurrent flows) QC-SH has high variance, standard deviation and mean delay. This can be explained by the extra overhead resulting from game computation, evaluation, and analyzing times.

Fig. 5.8 shows the performances of the proposed QC-SH algorithm in terms of the number of concurrent flows compared to the Parallelism approach using 4 servers. Four performance metrics are considered: a) the percentage of packets that exceed their deadline (Fig. 5.8(a)), b) the delay of processing flow number 2 (Fig. 5.8(b)), c) the number of rounds to process all pakets from each of 200 concurrent flows (Fig. 5.8(c)), and d) the delay of processing each flow (Fig. 5.8(d)). We observe the QC-SH works better with 4 servers (with an improvement of up to 4% in packets that respect their maximum delay, 600s in delay of processing all concurrent flows, one processing round per packet and 3s of processing delay per packet compared to QC-SH with one server). We also note that QC-SH performs better than the Parallelism solution Ding *et al.* (2018) with an improvement of up to 2% in terms of the number of packets that preserve their maximum delay, up to 250s in delay of processing all concurrent flows, two processing rounds per packet and 3.5s of processing delay per packet. Therefore, our approach performs better with multiple servers.

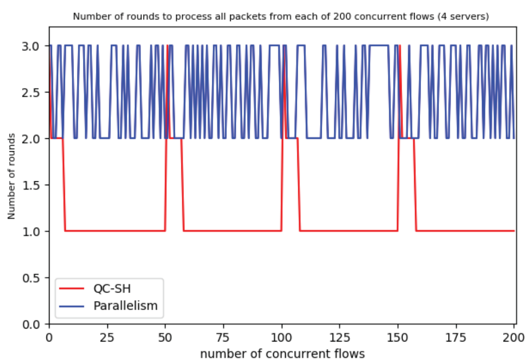
In Fig. 5.9, we study statistical performances of the proposed QC-SH in terms of the number of concurrent flows compared to the Parallelism solution Ding *et al.* (2018) using four servers in terms of a) the variance (Fig. 5.9(a)), b) the standard deviation (Fig. 5.9(b)), and c) the mean delay of processing of all flows (Fig. 5.9(c)). We see an improvement of QC-SH with 4 servers of 83% in variance, 90% in standard deviation and 88% in mean delay compared to QC-SH with one server. In addition, QC-SH performs better than the Parallelism solution Ding *et al.*



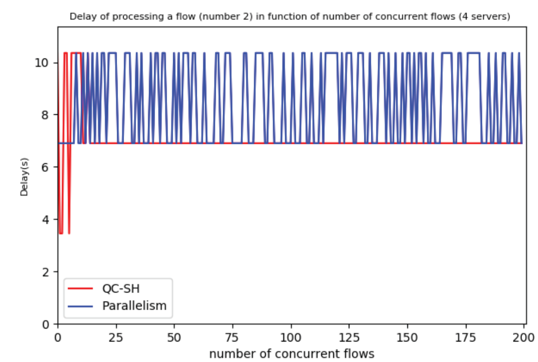
a) Percentage of packets that exceed their deadline in function of number of concurrent flows (%)



b) Delay of processing flow number 2 in function of number of concurrent flows (second)



c) Number of rounds to process all pakets from each of 200 concurrent flows



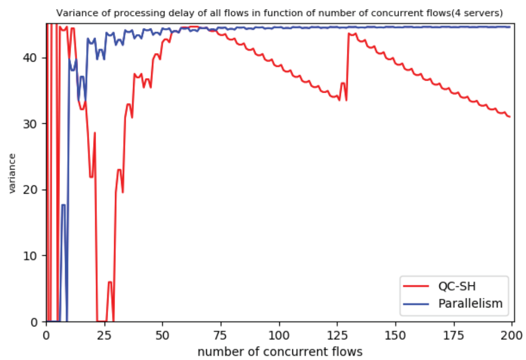
d) Delay of processing each flow in function of number of concurrent flows (second)

Figure 5.8 QC-SH performances in function of number of concurrent flows (4 servers).

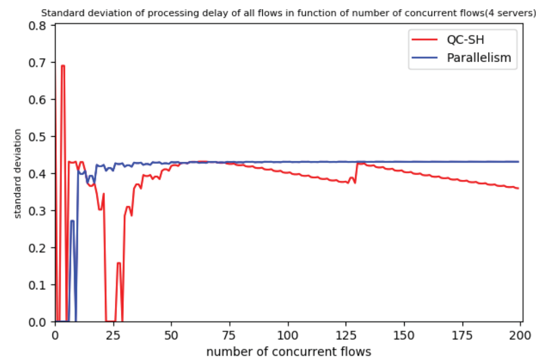
(2018) in terms of the fairness of processing flows with lower variance, standard deviation and mean delay for different numbers of concurrent flows.

5.8 Conclusion

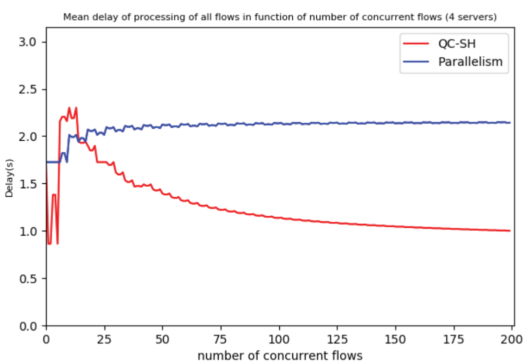
In this paper, we proposed a new probabilistic queuing model for concurrent smart home network traffic over different communication channels/ports, to provide some fairness in processing concurrent flows and increase the number of packets that meet their deadline while decreas-



a) Variance of processing delay of all flows in function of number of concurrent flows (second)



b) Standar deviation of processing delay of all flows in function of number of concurrent flows (second)



c) Mean delay of processing of all flows in function of number of concurrent flows (second)

Figure 5.9 Statistical performances for QC-SH in function of number of concurrent flows (4 servers).

ing the total processing delay. We tested our solution with 4000 network packets and 200 concurrent flows using one and four servers. Then, we compared it to the recent mono-processing and multiprocessing based scheduling solutions for each criterion. Our experimental results demonstrated that the proposed algorithm outperforms the current solutions in almost the totality of criterion. Future work includes an improvement of the proposed QC-SH mechanism to bypass the congestion problem for a queue with a limited size since packets from the loosing bidders remain in the gateway buffer. An integration of the proposed model into a SDN controller will also be considered.

5.9 Acknowledgment

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CHAPTER 6

CRITICAL DISCUSSION OF SOME CONCEPTS OF THE THESIS

The general objective of this thesis has been to design a new network framework for the enhancement of smart community and smart home networks to make them more efficient and more accessible. Our proposed general methodology consists of three themes, which we covered in this work: Chapter 3 presented a new routing solution for heterogeneous wired-wireless smart community network that determines the minimal cost between all pairs of nodes in the network taking into account the different types of physical accesses and the network utilization patterns. Chapter 4 introduced a new queuing model for multi-sourced smart home network traffic with mixed arrival distributions that makes a dynamic QoS-aware scheduling decision meeting their delay requirements while preserving their degrees of criticality. Finally, a new queuing model for concurrent traffic in smart home network was presented in chapter 5. Each theme is the subject of a separate published journal article to disseminate them as widely as possible. Below, we highlight the strengths and weaknesses of the proposed methods as reflected in each theme.

6.1 QoS-based routing in inter-SHNs

In Chapter 3, we defined a QoS-Aware Software-Defined Routing (QASDN) algorithm that uses Software-defined networking (SDN) technology and determines the minimal cost between all pairs of nodes in the inter-SHNs taking into account the different types of physical accesses and the network utilization patterns. The QASDN algorithm computes all wired-wireless paths between SHNs, determines the minimal costs of flows in terms of the bandwidth consumed by the APs and the packet loss and then, assigns optimal APs (or ARs) to cache data on the optimal path. This method has been defined in an article published by Elsevier in the Journal of Computer Networks and is the main contribution of this article. Our experiments show the proposed solution improves resource utilization up to 90%, and outperforms the traditional shortest cost based algorithm with a gain that reaches 13% for the majority of criteria, with

83% for distance, 77% for bandwidth and 51% for packet loss.

We compared our solution with the traditional CBSP algorithm that uses the Lagrangian Relaxation Based Aggregated Cost (LARAC) algorithm Juttner *et al.* (2001) as solution to solve the CBSP problem (Fig.3.6) in terms of the percentage of paths that meets all constraints for different numbers of nodes, the number of paths that fulfill each constraint obtained with QASDN over those obtained with the traditional CBSP algorithm for 14 tests and, the cache utility (CacheU) in Mbps obtained with QASDN and CBSP for different numbers of nodes. The traditional CBSP algorithm returns the optimal path for a single criterion (the delay) while increasing significantly the cost of the other criteria. On the other hand, QASDN algorithm maintains the four parameters in an acceptable rate and provides a gain in AP (or AR) resources up to 90%. Specifically, with QASDN (Fig.3.5) the majority of paths under threshold for each criterion can reach to 100%, however, it decreases when we increase the size of topology and, the average number of paths that meets the loss and the delay threshold (thr) is kept at a good rate (53%) for up to 50 nodes. Our QASDN solution do not consider the trade-off among the criteria, in fact, with a decrease in loss, bandwidth and distance criteria, there is an increase in the delay criterion (Fig.3.5, 3.9). In addition, QASDN addresses only smart community's internal traffic optimization problem and do not consider the egress router of smart community and its traffic engineering policies.

6.2 Scheduling with QoS and QoE in SHN

The second theme covered the issue of scheduling in smart home network, with the aim of offering better traffic processing by considering both the QoS and the QoE requirements. In Chapter 4, we defined a new queuing metric combining the ToS field and the maximum number of packets that can be processed by the system's service during the maximum required delay. This metric is used to make dynamic QoS-aware scheduling decisions which meet delay requirements of all SHN traffic generated with mixed arrival distributions while preserves their degrees of criticality. The proposed scheduling discipline is presented in QP-SH algorithm 4.1. This method has been defined in an article published by IEEE in the Journal of IEEE Access and is the main contribution of this article. Our experiments show the proposed solution achieves an improvement of 15% of packets that meet their priorities and 40% of packets that meet their maximum delays as well as an increase of 25% of packets processed in the system. We compared our solution with the existing scheduling methods Shah *et al.* (2019); Sharma *et al.* (2018); Benacer *et al.* (2018), in terms of the number of packets that exceed their maximum delays, the mean number of packets that do not respect their priorities, and the mean number of packets in the system. The curves obtained with our algorithm are under the curves obtained with the existing solutions for the majority of criteria. Specifically, the number of QP-SH based packets that violate their maximum delay and do not respect priority criterion decreases when we increase the arrival rate up to zero packets for arrival rates more than 40 packets/ms (Fig. 4.6). However, FIFO-prem based solution remains the optimal solution that guarantees priority criterion while increasing the delay since it is based only on priority (Fig. 4.7). In addition, when we increase the service time per packet, the performance of all solutions decreases and QP-SH maintains the lowest values except for FIFO-prem in priority criterion (Fig. 4.8). Theoretically, the proposed approach is promising and it outperforms the current solutions against almost all criteria by providing both QoS and QoE, which is an advantage that the other state-of-the-art methods do not possess. However, our current results showcase only our approach over simulating networking settings. A case study involving concrete streaming services with real network data, monitoring and user applications, combined with real QoS requirement specifications would actually show the contributions of the proposed approach in actual modern smart home networks.

6.3 Concurrent traffic scheduling in SHN

Since the dynamic nature of today's home network caused by the fluctuation of network traffic distributions has a direct impact on scheduling engines in terms of congestion and packets concurrency, an automated management of traffic loads within the home gateway by offering multiple concurrent access for the same channel/ethernet port is mandatory. Recent advances in optical, wireless and cellular modulation technologies have been made from the perspective of increasing the number of concurrents users per media access. Unfortunately, these solutions become less effective in delay for multi-channel/port concurrency issue and do not consider the fairness between traffic flows from the same class of service which makes them unsuitable for delay-sensitive applications. To address these limitations, we presented QC-SH, an innovative probabilistic queuing model for concurrent traffic in SHN (Chapter 5) which provides a fair scheduling between concurrent traffic belonging to different media access. To summarize, what we have proposed is a new queuing design based on the auction economic model of game theory and a free-overhead implementation model on both sides; traffic sources and the home gateway, without changing the structure of the IEEE 802.11 standard. The proposed solution is based on an analytic model for optimizing concurrent packet scheduling in a smart home network with mixed arrival distributions and different QoS requirements. This method has been defined in an article submitted to IEEE in the Journal of IEEE Transactions on Vehicular Technology and is the main contribution of this article. Our experiments show the proposed solution achieves an improvement of 14% of packets that meet their required delay and 57% of delay for different number of concurrent flows in the system.

We compared our solution with recent mono-processing and multiprocessing scheduling approaches Han *et al.* (2016); Ding *et al.* (2018), in terms of the percentage of packets that exceed their deadline, the delay of processing a single flow and, the delay of processing each flow. The results show that the proposed method is able to provide a lower delay for processing all flows and a lower number of packets that exceed their deadline, as a result of its fairness feature in order to provide a lower total processing delay for concurrent flows compared to the existing solutions (Fig. 5.6, Fig. 5.8). Specifically, when we increase the number of concurrent flows, both the variance and the standard deviation of the processing delay with QC-SH decrease while remaining under the curves of the existing solutions and, the processing delay of all flows will be close to the average, thus, the fairness feature of our solution makes it less sensitive to the fluctuation of the number of concurrent traffics (Fig. 5.7, Fig. 5.9).

The advantages of this method are that it is specific for smart homes, overhead-free and has a positive impac ton the performance of the scheduling engine compared to the existing solutions. More precisely, the specific traffic distribution in smart homes can be classified into three categories, as presented in Section 5.4, while in the general context like the Internet it is normal distribution which is hard to model and, the game theoretical model can be easily implemented in the home gateway serving a limited number of flows in the home. In addition, MAC layer Management and control packets are lightweight packets (Fig.5.2) compared to those of network layer which provide a communication with a negligible overhead Heydari & Yoo (2015).

The difficulty with QC-SH solution lies in the evaluation process which is based on the assumption that all packets are MTU-sized packets and the service follows a deterministic distribution. Also, flows may provide untrue information to gain advantage in the game. For example, some applications may set a lower maximum delay than necessary in the game. In addition, the congestion problem for a queue with a limited size should be addressed since packets from the loosing bidders remain in the gateway buffer.

CONCLUSION AND RECOMMENDATIONS

M2M and IoT technologies are presenting several new challenges for relevant next-generation communication. The expected explosion in the number of IoT objects, especially with the flourish of smart applications that provide services in different areas like industrial, healthcare and smart city domains, requires creating a congestion-free efficient automatic exchange of information between devices, machines and systems. In particular, Smart home networks are facing an ever-increasing traffic demand to manage a network of electronic and electrical devices in a special heterogenous wired-wireless network structure with a high traffic fluctuation and resource-constrained systems. Designing and implementing such networks involves big network transformation and several resource requirements to match supply and demand while meeting the preferences and needs of users. This may not fit the limited-capacity devices as well as the total available bandwidth in SHNs. A combination of cost-effective heterogenous multi-constrained routing protocol, efficient QoS and QoE-based scheduling system and smart concurrent-traffic queuing strategy is required to enhance routing and queuing for future smart home architectures.

In this work, we proposed a QoS-Aware Software-Defined Routing (QASDN) model for optimizing dynamic QoS-based data streams in a software-defined smart community network. We formulated a QoS-based routing optimization problem as constrained shortest path problem, and then proposed a wired-wireless routing model called H-LARAC that considers the different types of physical accesses in the inter-SHNs. We presented also a new solution called EH-LARAC that determines minimal cost flows between all pairs of nodes in the inter-SHNs, and then extended it in a model called EHM-LARAC by considering different constraints in the calculation of the optimal path and combining network QoS (delay, bandwidth, loss and distance). We further enhanced our solution using an optimal caching assignment method called P-OFTRE that minimizes memory consumption at the access point level.

In a next step, we proposed a new Queuing model for QoS-level Pair traffic in smart home network called QP-SH to increase the number of packets that meet their deadline while preserving their degree of criticality. The proposed QP-SH model includes a new queuing metric combining QoS and QoE requirements for SHN and a dynamic queuing algorithm for smart home network traffic generated by heterogeneous sources and with mixed-arrival distribution.

Finally, we proposed a new probabilistic queuing model for single QoS-level concurrent traffic in smart home network called QC-SH. The QC-SH model provides some fairness in processing concurrent traffic over different communication channels/ports, increases the number of packets that meet their deadline and decreases the total processing delay. We further proposed a free-overhead implementation model for QC-SH on both sides; traffic sources and home gateway.

QASDN experimental results made from 14 network topologies and a random number of nodes (up to 400 nodes), demonstrated that the proposed inter-SHNs routing algorithm outperforms the traditional shortest cost-based algorithm in almost the totality of constraints. In addition, simulation results of 1000 network packets generated with different distributions, show the advantage of the proposed QP-SH model that provides better results in terms of delay, QoS and QoE compliance comparing traditional scheduling solutions. Moreover, test results made with 4000 network packets and 200 concurrent flows using one and four servers demonstrated that the proposed QC-SH approach outperforms the recent mono-processing and multiprocessing based scheduling solutions in delay and QoS requirements.

In future work, we will focus on: i) applying a traffic differentiation method to the proposed QASDN model in order to consider the trade-off among the criteria since the delay could increase when loss, bandwidth and distance decrease, that is, delay-sensitive traffic would be treated in a higher priority by APs (or ARs), ii) generalizing our QASDN solution to incorporate the egress router of smart community and its traffic engineering policies rather than considering only smart community's internal traffic, iii) improving the proposed QP-SH model by using different packet sizes and different service distributions, and iv) integrating our QP-SH model into an SDN controller to bypass the congestion problem for a queue with a limited size since packets from the loosing bidders remain in the gateway buffer.

Furthermore, our current results showcase only our approach over simulating networking settings, which will also be extended to incorporate actual modern smart home networks with real network data, monitoring, and user applications, combined with real QoS requirement specifications.

7.1 Major contributions

The major contributions of this thesis are:

1. **Hybrid LARAC (H-LARAC), Extended Hybrid multi-constraints LARAC (EHM-LARAC) and, Extended Hybrid LARAC (EH-LARAC):** Wired-wireless routing model that considers the different types of physical accesses, the different QoS constraints (delay, bandwidth, loss and distance) in the calculation of the optimal path and determines minimal cost flows between all pairs of nodes in the inter-SHNs.
2. **P-OFTRE Offline Traffic Redundancy Elimination (P-OFTRE):** An optimal caching assignment method that minimizes memory consumption at the access point level.
3. **QoS-Aware Software-Defined Routing (QASDN):** An SDN-based routing algorithm for smart community network that combines the benefits of H-LARAC, EH-LARAC, EHM-LARAC and P-OFTRE solutions.
4. **SHN traffic modeling:** A comprehensive study to model and characterize the different SH traffic sources and distributions.

5. **QoS-level Pair traffic scheduling in smart home network (QP-SH):** QoS and QoE based scheduling model for SHN traffic with mixed-arrival distribution using a new queuing metric that combines QoS and QoE requirements for SHN.
6. **QoS-level concurrent traffic in smart home network (QC-SH):** Queuing model for SHN that provides some fairness in processing concurrent traffic over different communication channels/ports, increases the number of packets that meet their deadline and decreases the total processing delay. This model uses a novel algorithm based on an auction economic model to fairly process concurrent traffic in SHN.
7. **An overhead-free QC-SH implementation design:** An implementation design of QC-SH approach on traffic sources side and the home gateway side, without changing the structure of the IEEE 802.11 standard.

7.2 Articles in peer-reviewed journals and conferences

1. Attia, Maroua Ben, Kim-Khoa Nguyen, and Mohamed Cheriet. "QoS-aware software-defined routing in smart community network." Computer Networks 147 (2018): 221-235.
2. Attia, Maroua Ben, Kim-Khoa Nguyen, and Mohamed Cheriet. "Dynamic QoS-aware Queuing for Heterogeneous Traffic in Smart Home." 15th International Wireless Communications & Mobile Computing Conference (IWCMC 2019 QoS and QoE Workshop): 1287-1292
3. Attia, Maroua Ben, Kim-Khoa Nguyen, and Mohamed Cheriet. "Dynamic QoE/QoS-aware Queuing for Heterogeneous Traffic in Smart Home." IEEE Access 99 (2019):1-1. 10.1109/ACCESS.2019.2914658
4. Attia, Maroua Ben, Kim-Khoa Nguyen, and Mohamed Cheriet. "Concurrent Traffic Queuing Game in Smart Home." 15th International Conference on Network and Service Management (CNSM 2019 Mini-Conference): 1287-1292

5. Attia, Maroua Ben, Kim-Khoa Nguyen, and Mohamed Cheriet. "Dynamic QoS-aware Scheduling for Concurrent Traffic in Smart Home." submitted to IEEE Transactions on Vehicular Technology (19 July 2019).

APPENDIX I

SIMULATION WITH THE VIRTUAL GATEWAY

1. Test with Mininet

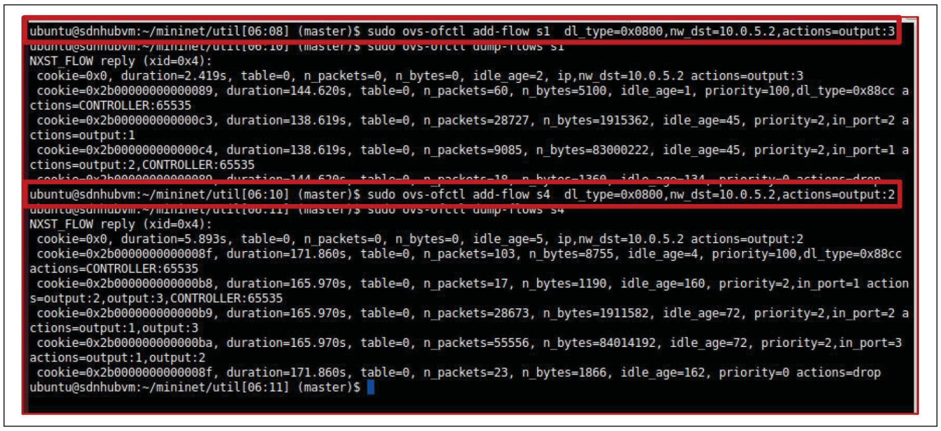

Figure-A I-1 Test with mininet 1.

2. Test with a virtual gateway

The topology is given by the following figure:

OpenWrt configuration:

- Install OpenWrt VM + Ovs
- Configure OpenWrt to support 3 lan interfaces to communicate with home devices and 1 wan interface to communicate with the cloud (and then the controller)
  - Wan: 1 bridged connection with the dhcp protocol
  - Lan: internal "intnet" connection with 3 ports and static IP addresses
  - Configure the firewall and the dhcp of each lan connection

Configuring Home Appliances with OpenWrt:

- Create 3 virtual machines; Home_PC1, home_PC2, home_PC3

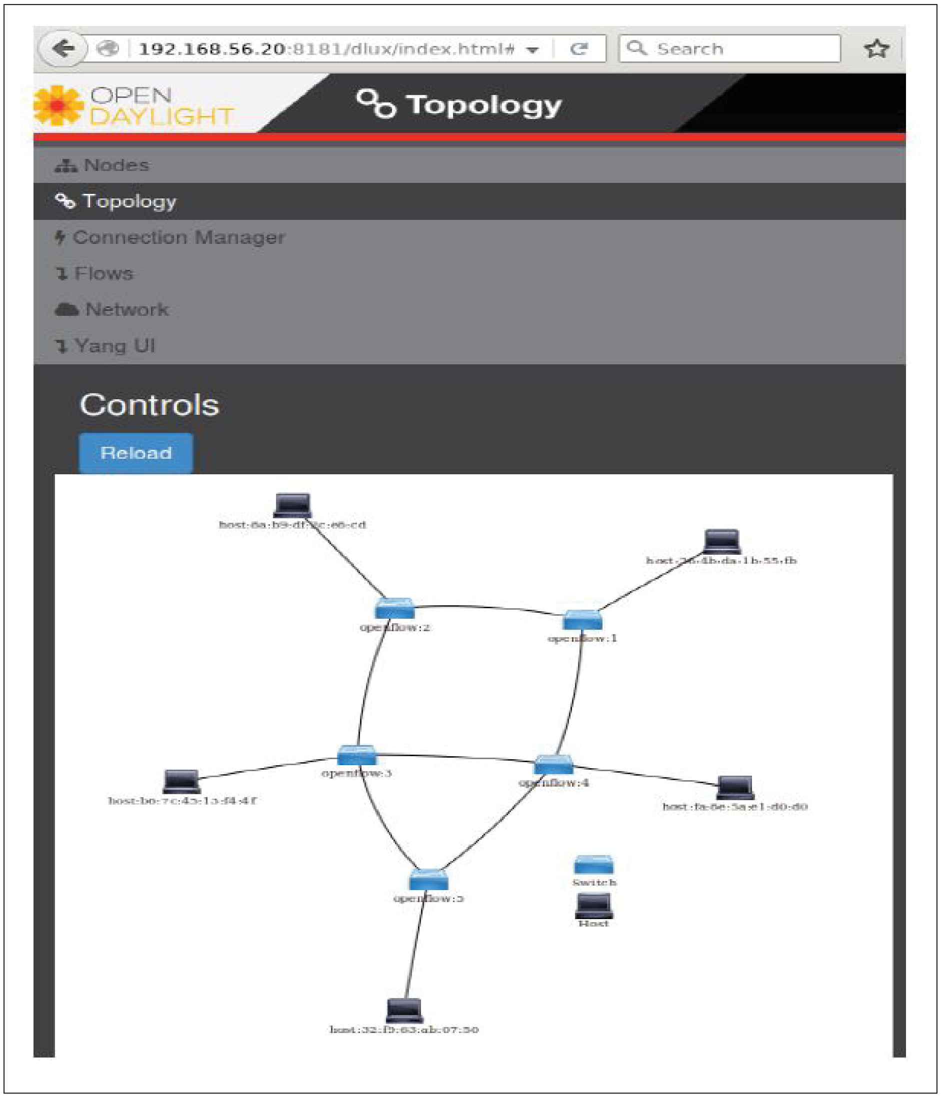

Figure-A I-2 Test with mininet 2.

- Configure each virtual machine to connect to the same OpenWrt internal network ("intnet") and with the dhcp protocol so that OpenWrt assigns them a dynamic IP address to connect to the Internet.

Configuring ODL with OpenWrt:

- Install ODL in a VM with bridge mode and add the dhcp protocol
- Start the controller: ./bin/karaf

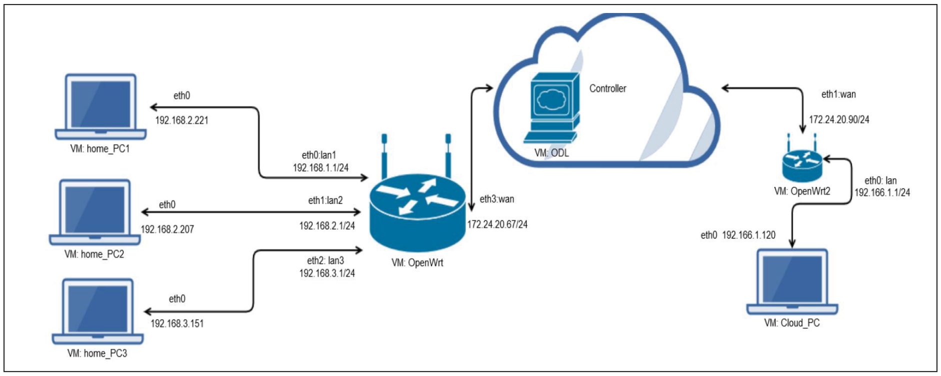

Figure-A I-3 Topology with virtual gateway.

Figure-A I-4 OpenWrt with virtual gateway.

- Install the ODL GUI: feature: install odl-restconf odl-mdsal-apidocs odl-dlux-all
- Configure OVS to communicate with the controller and to control the network through ODL

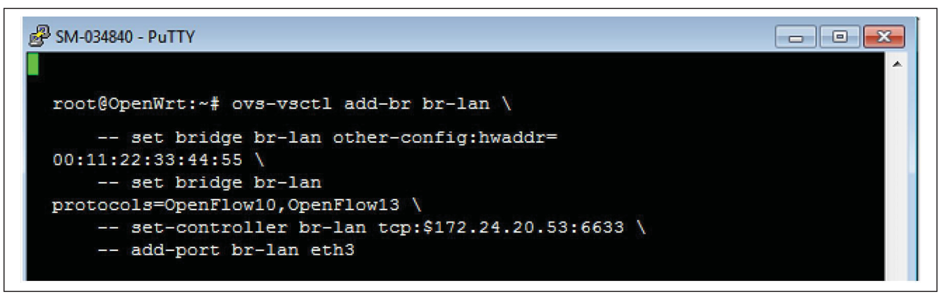

Figure-A I-5 OVS with virtual gateway.

APPENDIX II

OVS DEPLOYMENT IN A REAL ROUTER

1. Installing OpenWrt and OVS

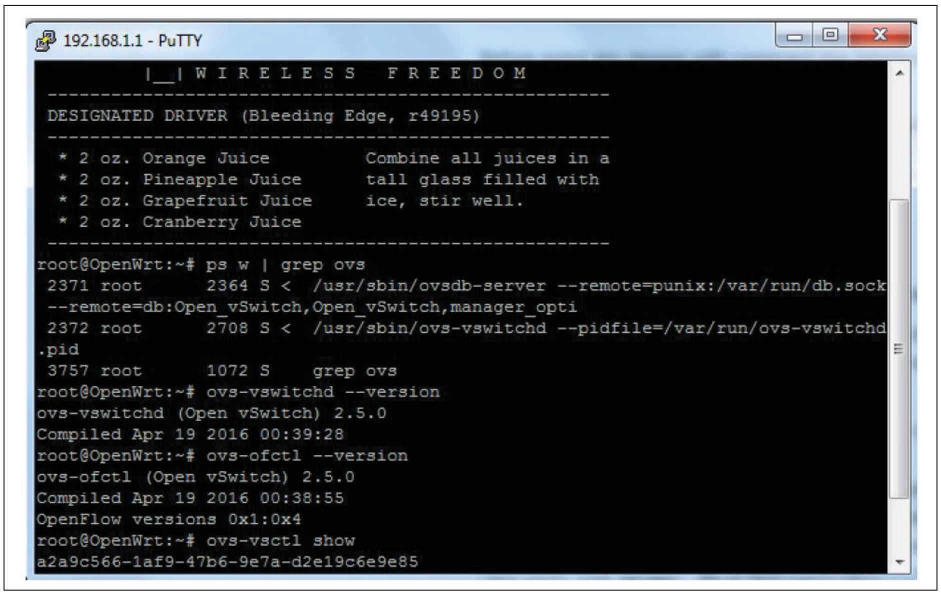

Figure-A II-1 OVS with real gateway.

The SDN Controller:

./bin/karaf (VM with IP 192.168.1.110)

opendaylight-user@root> feature:list | grep dlux

opendaylight-user@root> feature:install odl-dlux-all

opendaylight-user@root> feature:install odl-dlux-core odl-dlux-node odl-dlux-yangui odl-dlux-yangvisualizer odl-l2switch-switch-ui

2. Test in a real environment

OVS configuration:

ifconfig ovs-system up &&ovs-vsctl del-port brOVS eth0.2 && brctl delif br-lan2 eth0.2 &&

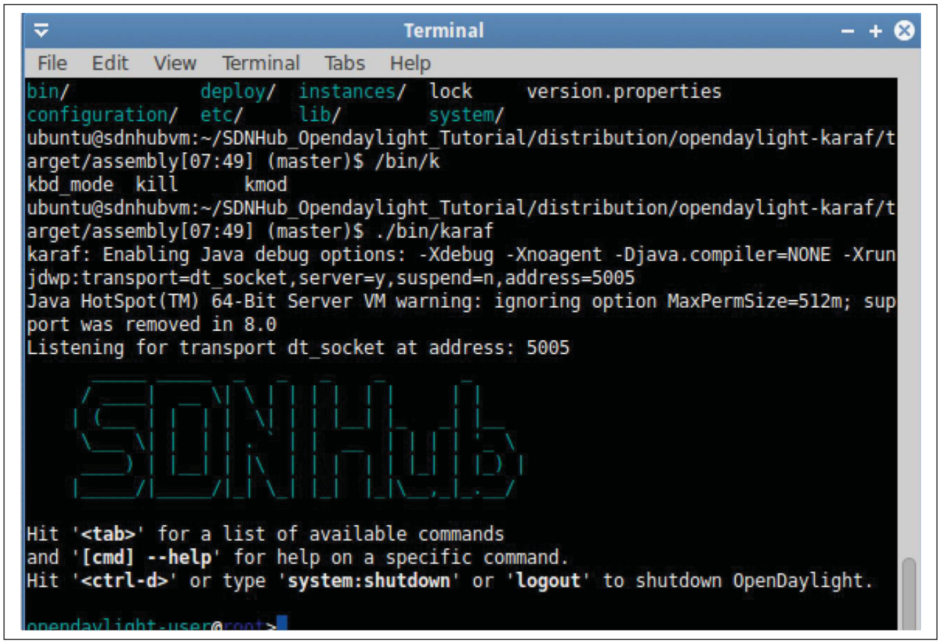

Figure-A II-2 ODL.

ifconfig br-lan2 0.0.0.0 && ifconfig brOVS 192.168.2.1 && ovs-vsctl add-port brOVS eth0.2 && ifconfig brOVS up

Adding flows:

root@OpenWrt:~# ovs-ofctl dump-flows brOVS

NXST_FLOW reply (xid=0x4):

cookie=0x0, duration=17.522s, table=0, n_packets=0, n_bytes=0, idle_timeout=120, idle_age=17, priority=1,ip,in_port=2,nw_src=192.168.2.185 actions=NORMAL (hardwarepath)

cookie=0x0, duration=5.146s, table=0, n_packets=0, n_bytes=0, idle_timeout=120, idle_age=5, priority=1,ip,nw_dst=192.168.2.185 actions=output:2

Test before and after adding flows:

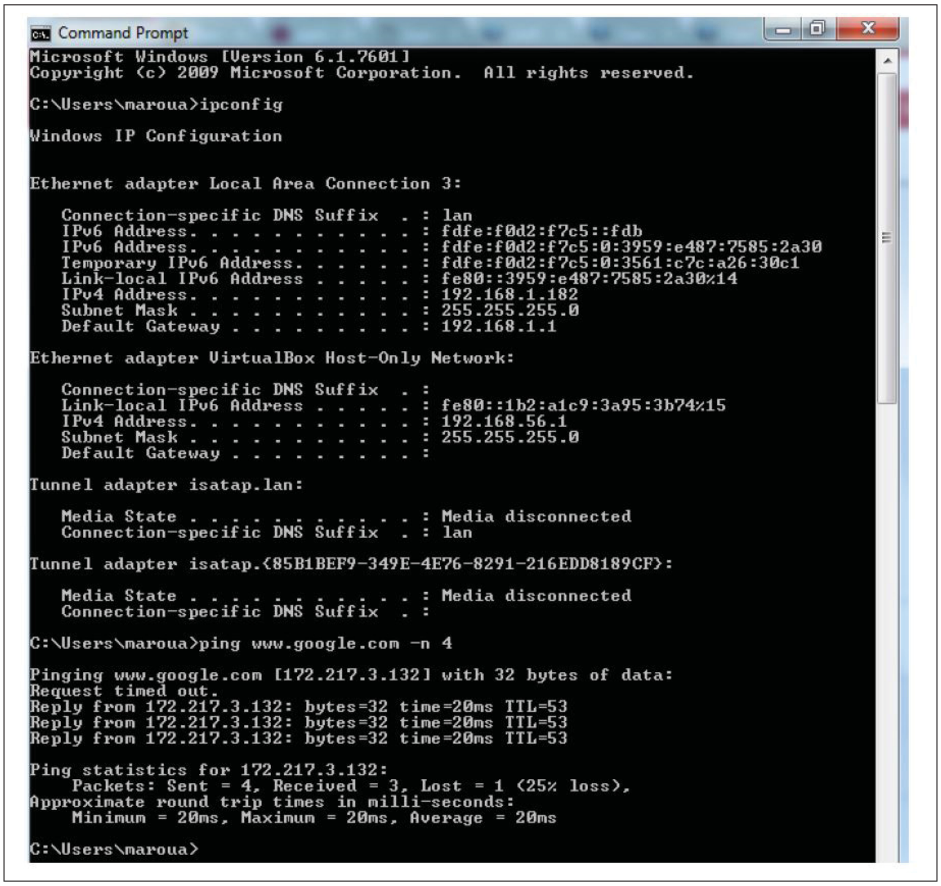

Figure-A II-3 Test with a wired connection.

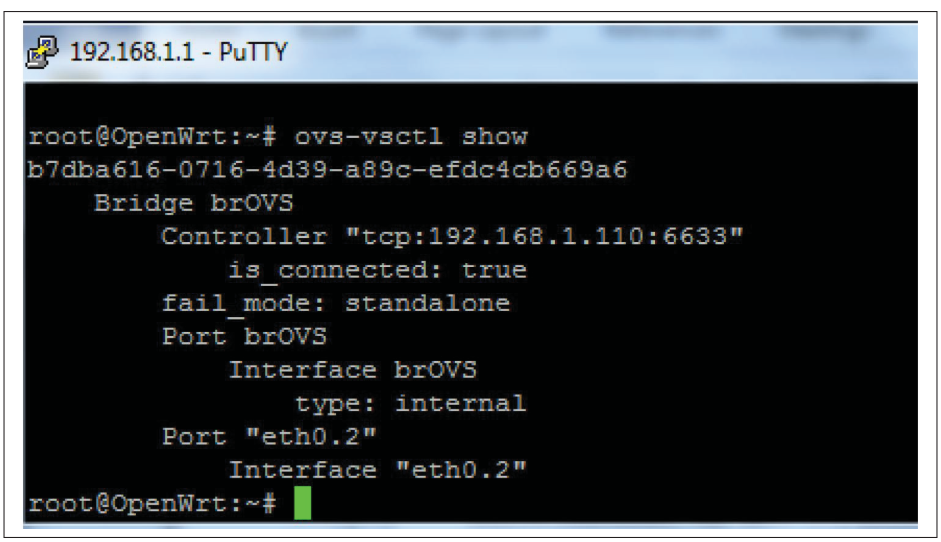

Figure-A II-4 OVS configuration.

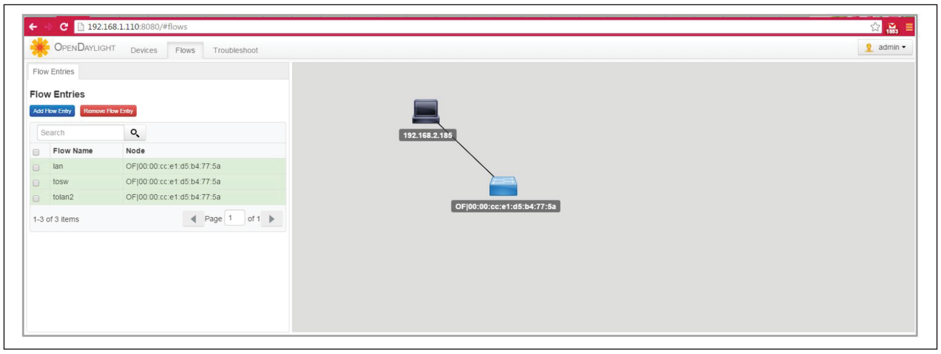

Figure-A II-5 Flow management with ODL.

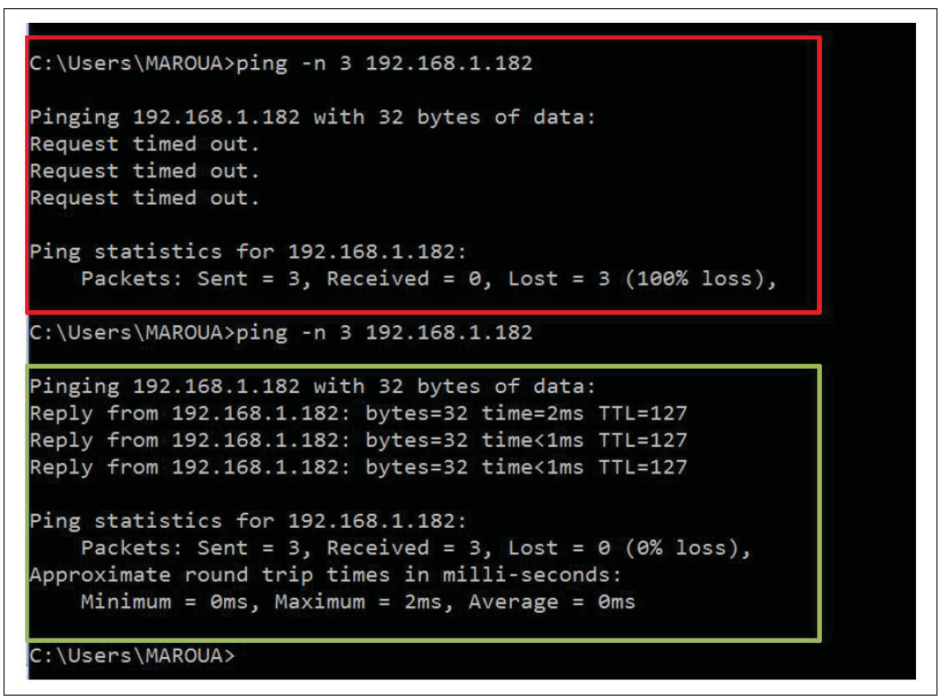

Figure-A II-6 Flow routing with OVS.

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