Integration of Network Coding, Spatial Diversity and Opportunistic Routing/Forwarding in Wireless Mesh Networks

by

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When I started doing my graduate studies, I had no clue what is that I am going to be doing for studies. I was quite confused, whether I wanted to spend my days in a dorm room reading documents late night, debugging my codes or did I wanted to be partying around with friends. Well it was quite a journey!!! Whether I would do it again if I can go back in time? Of course, I would not choose otherwise. I was lucky enough to be in Montreal, Quebec, during my studies. I love every bit of it, except for the winter!!!!! I would like to extend my thanks to my supervisor Prof. Dziong, for his enormous patience towards me. I think he put more time and effort that I have put to finish this work. I can't thank him enough, but thank you for those long hours of chatting we had. He is an amazing person, great mentor. Who had enormous patience, when nothing was working; I think for most of my work, part of credit goes to him. I would also like to thank my Co-Supervisor Prof. Fabrice Labeau for his support and encouragement. I would also like to thank Prof. Kadoch, Director, LAGRIT. I once had a small chat with him, that chat resulted me to develop a mechanism for network simulation monitoring where I can closely monitor the network and then I can read event, it's a painful process where I had to read lots of line of console output, but it works fine to detect events and observe the series of events. I would also like to thank all my friends at the LAGRIT and at the school.

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INTEGRATION OF NETWORK CODING, SPATIAL DIVERSITY AND OPPORTUNISTIC ROUTING/FORWARDING IN WIRELESS MESH NETWORKS

Mohammad Rizwan KHAN

RÉSUMÉ

Le réseau maillé sans fil constitue une réponse au problème du « dernier kilomètre ». Celui-ci nous offre en effet, un accès Internet bon marché, un déploiement facile et une grande couverture réseau avec moins de fils. Néanmoins, son débit limité est une barrière à son intégration aux applications de prochaine génération. Motivé par les caractéristiques et avantages de cette technologie, nous présentons une solution à ce problème de débit limité en tirant profit de son caractère de diffusion sans fil. Le codage réseau, la diversité spatiale et le routage/transfert opportuniste capitalisent sur la nature de diffusion des connexions sans fil pour améliorer les performances du réseau. Ces techniques ciblent différentes conditions de réseau et sont en général considérées séparément. Dans cette thèse, une intégration basée sur l'inter-couche (c.à.d. *cross-layer*) des trois techniques mentionnées est présentée. Cette intégration permettra d'accumuler leurs gains potentiels en utilisant la même pile de protocole réseau dans un réseau maillé sans fil. L'approche d'intégration proposée est basée sur une nouvelle métrique CDARM (Coding opportunity and Data rate Aware Routing Metric) utilisée pour la sélection d'itinéraire et sur une méthode de création des liaisons relais au niveau de la couche MAC. Pour exploiter la nature de diffusion, nous avons développé un protocole coopératif (CP_RL) intégrant ces différentes techniques. Un routage opportuniste est tout d'abord introduit dans le protocole coopératif par la création de liaisons relais au niveau de la couche MAC. Sur la base de ce protocole coopératif (CP_RL) et de la métrique de routage, le mécanisme de codage réseau y est ensuite intégré. Pour finir, une coopération entre le réseau et les couches MAC est mis en place. Les simulations numériques menées lors de cette étude ont montré une amélioration significative des performances du protocole intégré et ce, aussi bien en termes de débit que de fiabilité du réseau. Au meilleur de notre connaissance, cette thèse est la première tentative d'intégration du codage réseau (NC), de la diversité spatiale (CP) et des mécanismes de routage opportuniste (OR) dans la même pile de protocoles. Les avantages du protocole intégré peuvent être clairement observés à partir des résultats. On constate que l'amélioration de la performance varie faiblement dans un scénario à saut unique pour progressivement augmenter dans un scénario multi-saut (c.a.d. *multihop*). Cette thèse présente un cas d'étude important où nous préconisons d'exploiter aussi bien la nature de diffusion de la chaîne sans fil que l'architecture inter-couche (c.a.d. *cross-layer*) où les couches interagissent fréquemment les unes avec les autres au lieu de travailler isolément. Certes le protocole intégré nécessite des modifications dans la pile de protocole réseau. Mais ces modifications pourront être facilement incorporées dans les dispositifs de génération future.

Mots clés : codage réseau, diversité spatiale, opportuniste de routage, la création de liens sur la couche MAC.

INTEGRATION OF NETWORK CODING, SPATIAL DIVERSITY AND OPPORTUNISTIC ROUTING/FORWARDING IN WIRELESS MESH NETWORKS

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ABSTRACT

Wireless Mesh Network is an answer to the last mile problem. It offers easy deployment and provides coverage over large area with fewer wires. Nevertheless, its limited throughput is inadequate for next generation applications. Motivated by its features and advantages, we propose a solution to mitigate this problem of limited throughput by leveraging the broadcast nature of the wireless medium. In particular, network coding, spatial diversity and opportunistic routing/forwarding capitalize on the broadcast nature of the wireless links to improve the network performance. These techniques target different network conditions and usually are considered in separation. In this thesis a cross-layer based integration of the mentioned three techniques is presented to accumulate their potential gains using the same network protocol stack in wireless mesh networks. The proposed integration approach is based on a new CDARM metric (Coding opportunity and Data rate Aware Routing Metric) used for the route selection and a method for creating relay links at the MAC layer. In particular to leverage on the broadcast nature we developed a cooperative protocol, based on link creation at the MAC layer that introduces opportunism into the cooperative protocol. Based on this cooperative protocol and the routing metric, we integrate the network coding mechanism. Then we introduce cooperation between the network and MAC layers. The numerical study, based on the system level simulation results, shows significant improvement of the integrated protocol performance in terms of network throughput and reliability over the individual mechanisms. To the best of our knowledge this dissertation is the first attempt to integrate network coding, spatial diversity and opportunistic routing/forwarding mechanisms in the same protocol stack. The integrated protocol requires modifications into the network protocol stack that can be easily incorporated in future generation devices.

Keywords: Network coding; Spatial diversity, Opportunistic routing, Link creation at MAC layer.

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LIST OF ABREVIATIONS

WMN	Wireless mesh network
NC	Network coding
SD	Spatial diversity
OR	Opportunistic routing
CP	Cooperative protocol
CP_RL	Link creation at the medium access control layer
CDARM	Coding opportunity and data rate aware routing metric
MIQ	Modified Interference Queue
CW	Contention Window
SIFS	Short Inter-Frame Space
DIFS	Distributed Inter-Frame Space
MAC	Medium Access Control Protocol
NAV	Network Allocation Vector
SNR	Signal to Noise Ratio
RREQ	Route Request
RREP	Route Reply
DCF	Distributed Coordinated Function
AODV	Ad hoc On-Demand Distance Vector
NTPD	Number of Transmission per Packet Delivery
INT	Integration of three broadcast based protocol
INT-C	Network and MAC layer cooperation enabled integration

INTRODUCTION

0.1 Motivation

Wireless technologies occupy major segments in the telecommunication industry. Wifi networks are promising for providing affordable internet access but their coverage limitations is a significant drawback since in order to provide continuous coverage, the access points need to be placed with high density, which is quite expensive. Wireless Mesh Networks (WMN) constitutes an attractive alternative especially in less populated areas. This is due to larger coverage of the access points where the mesh routers are placed at the boundaries of the access points (AP), the users can connect to the mesh routers in the event it is outside of the coverage of the AP connected to the wired network. However, there is a growing number of applications requiring high throughput such as live video, sharing large files, transfer of high definition multimedia to entertainment devices in homes, to mention a few. The current wireless mesh networks struggle to provide the demanded high throughput due to the multihop connections, broadcast nature of transmission medium, and channel dynamics.

While the traditional mechanisms coping with these issues mask the broadcast ability, more recent research starts to leverage this broadcast ability instead of treating it as an adversary. In particular, there are three promising mechanisms belonging to this category: Network Coding (NC), Spatial Diversity (SD) and Opportunistic Routing (OR). These mechanisms have been developed in isolation to leverage the broadcast capability of the wireless channel. Motivated by the gains, in terms of network throughput and data delivery ratio, from the NC, SD, and OR mechanisms developed in isolation, in this work we study the gains resulting from the integration of these three mechanisms in the same protocol stack.

0.2 Problem overview and objectives

NC works in the Shim layer between Network and Medium Access Control (MAC) layers (Katti et al., 2008), (Ho et al., 2004), (Katti, 2008), (Ahlswede et al., 2000). By mixing multiple packets together through some algebraic operation, it requires fewer transmissions which improves the performance. SD has been proposed to overcome the detrimental effects of fading and interference (Foschini et al., 1998), (Telatar et al., 1999). To realize the gain from SD, cooperative protocols (CP) have been proposed (Laneman et al., 2004), (Sendonaris et al., 2003) as a feasible alternative to MIMO techniques that are not always feasible due to space constraints of the device (Sadek et al., 2010). In CP, nodes in the vicinity of the transmitter and receiver (referred as relays) help in the transmission by forming a virtual antenna array. In the remainder of this thesis, the term CP is used in the sense of SD. Opportunistic Routing (OR) selects a subset of neighboring nodes which are closer to the destination than itself to capitalize on the broadcast nature of the links (Biswas et al., 2005), (Yuan et al., 2005). More recent work, (Rozner et al., 2009), indicates that the divergent paths and duplicate transmissions can be suppressed by selecting the next hop forwarder that is not based only on proximity to the destination but also on the inter-node distance among the next hop nodes. In (Luk et al., 2008), OR protocol for WMN has been analyzed with numerical simulations. While the objective of the NC, CP and OR protocols are the same (reducing the number of transmission by leveraging on the broadcast nature), they are usually considered in separation and the related protocols are quite different.

Now a question may be posed, whether one can integrate these three mechanisms in a common network protocol stack to accumulate the gains they offer. The main challenge is to bring these mechanisms into a single platform, so that the gain from one mechanism does not sabotage the gains from another mechanism, i.e., to create a cohesion in the functioning of these three mechanisms. In order to realize this, several issues need to be addressed and resolved, the main being: selection of relay nodes for cooperation, detection coding opportunity along the route, expediting coded packets transmissions, and improving the spectral efficiency. Also it is necessary to assess how far the accumulated gain from the sum of the individual gains is, since each mechanism can work optimally under different network characteristics. Solving the mentioned challenges and issues constitutes the objectives of our work.

0.3 Novelty and contributions

A new cross layer approach is proposed to realise the integration of the three broadcast based techniques. To the best of our knowledge, no prior attempts have been made to integrate these three mechanisms on to the same network protocol stack. Our approach is based on a new metric, Coding and Data Rate Aware Routing Metric (CDARM), used for the route selection. The CDARM metric defines where the cooperation and network coding are possible and beneficial. Also a relay link creation mechanism is introduced at the MAC layer. This mechanism uses a relay node when a direct link is weak and employs opportunistic forwarding. One of the distinct features of the integrated protocol stack is that the new metric CDARM, combines the link capacity, topology, traffic load and interference information together in a unified manner. Another important feature is cooperation among the network and MAC layer. The main contributions of the thesis are summarized as follows:

- A new routing metric is proposed (CDARM) that detects coding and cooperation opportunities;
- A MAC layer relay link creation method is devised that splits a link into two shorter links at the MAC layer on the fly, in an on demand fashion. This link creation at the MAC layer introduces opportunism for cooperative protocol into the network protocol stack. It is based on the MAC layer handshake control packet exchange. It results in improvement of the network throughput for cooperative protocol;
- A new form of cooperation between MAC and network layer is introduced. In this form of cooperation the network layer and MAC layer communicates frequently. This communication between MAC and network layer is used by the network layer to learn about the neighboring channel condition; where it stores these information is a data structure at the network layer. Cooperation among the network and MAC layer is extremely important as they are dependent on each other. This cooperation, among the two layers does not incur any extra overhead in terms of communicating meta data to the neighbours, as it is done by snooping on the channel in promiscuous mode as well as the

exchange of the network layer control packet which is used for conveying the meta data to estimate the metric. This cooperation facilitates the route and data rate selection for sending data packets at the MAC layer;

- The fourth contribution of this dissertation is the integration of NC, CP and OR protocol on to the network protocol stack for WMN. This integration is based on a new routing metric (coding and data rate aware routing metrics, CDRAM) and CP_RL. This is the first version of the integrated protocol, and the second version is where we have network and MAC layer cooperation enabled integration. The simulation results show that a significant gain can be achieved in terms of network throughput, delivery ratio and number of transmission required per packet delivery;
- A new network allocation vector(NAV) update procedure is devised for multi-rate wireless networks;
- Detailed modified network protocol stack for integration of the three broadcast based techniques is developed.

0.4 Contents

In order to facilitate reading the thesis, below we summarize the content of chapters.

Chapter 1: LITERATURE REVIEW
In this chapter the previous works related to integration of the various broadcast based techniques are presented. We underline the limitations that we tried to overcome in the proposed integrated protocol.

Chapter 2: INTEGRATED PROTOCOL DESIGN
In this chapter the main mechanism of the proposed integrated protocol are presented. First, in Section 2.1, the basic building blocks (NC, CP and OR protocols) of the proposed protocol are described and the gain from each element is explained. Then, the important novel link creation mechanism at the MAC layer is detailed in Section 2.2, where opportunism has been

introduced into the CP protocol. Introducing opportunism into the CP protocol improves its performance. The integrated protocol functioning is presented with the help of a diamond topology example in Section 2.3. In Section 2.4, the novel CDARM node-link metric, used in the integrated protocol for choosing paths that maximize the coding opportunities, is introduced. The importance of the CDARM metric is that it selects routes as well as relay nodes based on coding opportunities and also it takes the data rate of the links into consideration which is crucial for multi-rate network. Then an algorithm for the metric estimation is detailed in Section 2.5. The assumptions made for the purpose of implementing the integration are described in Section 2.6.

Chapter 3: DESIGN AND IMPLEMENTATION DETAILS

Integrated protocol design objectives and challenges are identified in Section 3.1. In particular, in order to realize integration of the three mechanisms (NC, CP and OR), some new functionality or modules have to be introduced in the network protocol stack. For ease of explanation, the modifications in the network protocol stack are described using the layered architecture structure. Section 3.2 describes the network layer modifications. First, in the RREQ (Route Request) part, judicious processing of the network layer control packets is detailed. Then, in the RREP (Route Reply) part, the influence of the proposed metric on the route selection process is described. In Section 3.3, it is described when link creation at MAC layer takes place and how network layer copes with this phenomenon. Section 3.4 describes how the MAC and network layer cooperate to leverage the broadcast nature of the wireless channel. Then MAC layer modifications are detailed in Section 3.5. In particular, the MAC header modifications are detailed in Subsection 3.5.1. The new NAV (network allocation vector) update procedure is described in Subsection 3.5.2. The queuing mechanism and coding policy are described in Subsection 3.5.3, where three separate queues usage is advocated and the priority order is defined. In Subsection 3.5.4, the procedure for successful/unsuccessful decoding of the coded packets and retransmissions is described. In order to maximize the coding chances, network coded packets need to be prioritized over non-coded packets. The packet prioritization which is done within the node and among the nodes is described in Subsection 3.5.5. The physical layer modifications required for the CP protocol are detailed in Section 3.6. The overall integrated protocol architecture with modules interaction description in the protocol stack is given in Section 3.7.

Chapter 4: PERFORMANCE EVALUATION OF THE INTEGRATED PROTOCOL
In this chapter the results from the packet level simulator are presented. First, in Section 4.1, the considered topologies are described and then the considered performance metrics are defined. In Section 4.2, the network throughput of the integrated protocol is compared with NC, CP, CP_RL, and the traditional hop based protocol. Then, in Section 4.3, the delivery ratio of data packets is compared. Section 4.4 presents the comparison of the number of transmission required per packet delivery is presented for the considered protocols. In Section 4.5, the distribution of different mechanism usage in the integrated protocol is analysed. In Section 4.6, we present comparison between the traditional packet forwarding and MAC and network layer cooperation enabled packet forwarding in order to advocate enabling the cooperation between MAC and network layer. In Section 4.7, a table 4.9 is provided where the gains from integration and the other mechanisms considered in isolation are compared.

At the end we draw conclusion based on the simulation results and indicate possible future direction of the work presented in this dissertation.

CHAPTER 1

LITERATURE REVIEW

In this chapter, first the recent broadcast based protocols are presented separately. For each individual mechanism the state of the art is described. Then the state of the art for integrated protocols is presented for several issues related to the thesis content. At the end of this chapter a table is presented that summarise the limitations of the works presented in the literature.

1.1 Opportunistic Routing Protocols

In (Zhao, et.all 2017) authors presented the opportunistic routing protocol from reliability and energy efficiency perspective, where the metric is based on the ETX metric which is suitable for single data rate(base rate). Their results shows comparison with traditional 802.11 load balanced routing for low power and lossy networks. In (Darehshoorzadeh et. al, 2016), authors present a discrete time Markov chain as a general model for opportunistic routing protocol's performance evaluation. They presented their model and validated this model with NS-2 based simulations. In (Darehshoorzadeh et. al., 2012), distance progress based opportunistic routing (DPOR) is presented. They presented a new metric which is based on the distance from a node to the destination as well as link delivery probabilities. The authors show that with their algorithm the performance is almost the same as optimum candidate selection, while DPOR requires less meta data to be communicated as well as faster running time.

In (LV, et.al., 2016) authors propose a new mechanism for coordination among the forwarding nodes. The authors present a mathematical model for expected coordination delay (ECD) and show that their model reduces the coordination delay among the forwarding nodes as compared to classical EXOR (Biswas. S, et.al., 2005).

1.2 Cooperative Protocols

In (Asaduzzaman et.al., 2011), instantaneous channel measurement based cooperation selection procedure has been presented, which can improve systems spectral efficiency. They authors showed that both the cooperation selection procedure and the relay selection procedure can be carried out using the same control signals. In (Elhawary, et.al, 2011) an energy efficient cooperative protocol has been proposed, which also improves the delivery ratio of the data packets. The authors also suggest that in the grid topology their scheme results in increased energy saving and delivery ratio as compared to the random topology. An analytical model for energy consumption, end-to-end robustness of the data loss as well as the capacity has been presented. In (Xu, et.al., 2011) authors present ARQ based wireless cooperative protocol. This protocol is based on channel estimation.

In (Escrig, 2011) the authors presented a receiver initiated cooperative protocol, where the destination/receiver node selects a single best relay based on the offline learning about the neighbors and for each source it maintains the best relay node based on the channel condition. This work is focused on the MAC layer and on a single wireless link between a single source and a destination. In (Kim, et.al,. 2013) the authors presented spectrally efficient protocol for half-duplex multi-relay systems, where the direct link between the source and the destination is unavailable. In (Sheng et.al,. 2015) power allocation method for optimizing the decode and forward cooperative transmission from source and relay nodes has been presented that reduces the total power consumption while maintaining the required quality of service (QoS). An energy efficient relay node selection mechanism is also presented for multiple cooperative nodes within the network. For wireless multimedia networks, the authors advocate the non-uniform power usage to various cooperative transmitters.

In (Kakitani, et.al., 2012) the performance of the amplify and forward (AF) and decode and forward (DF) are presented from energy efficiency perspective. They concluded that to achieve the maximum energy efficiency different rates should be allocated to the users in asymmetrical network topology and also the most efficient protocol depends on the relative position of the users in the network topology. They also asserted that when the users are close in terms of distance, DF protocol is more efficient that AF protocol.

1.3 Network Coding Protocol

In (Long, et.al., 2017), authors presented coding aware routing protocol. A back-pressure based network coding aware routing has been presented, where the authors advocates changing the path when the coding opportunity ceases. As it is well known that the coding opportunities are dependent on flows, there may be better paths when the coding opportunities at the considered paths ceases. In that context, authors proposed to employ back-pressure based network coding aware routing protocol. In (Shijun, et.al., 2017), a network coding design from energy saving perspective has been presented. Authors suggested that the network coding scheme results in better energy performance, as compared to non-network coding schemes, when the number of mobile users in the network is large. They also emphasized that in order to minimize the energy consumption in NC based protocols the relay nodes should be placed at the midpoint between the mobile users and the base stations.

1.4 Integration of different broadcast based protocol

1.4.1 Integration of OR with NC

The MORE protocol (Chachulski et al., 2007), integrates the OR with intra-session NC protocols. The results show that MORE improves performance of the network when compared to the EXOR protocol (Biswas et al., 2005) by leveraging the spatial reuse and it also removes the need for global coordination among the next hop forwarders. Nevertheless it requires complex associated hardware (Kim et al., 2013). Also the experiments have been conducted for only fixed data rate. In (Yan et al., 2010) the authors present the CORE protocol that integrates the OR and inter-session NC. This protocol selects a group of forwarders which are close to the destination and the forwarding priority of these forwarder nodes are selected based on coding opportunities. It attempts to maximize the number of packets sent in each transmission. It is presented for fixed bit rate network, whereas multi-rate capability of the network is not considered. The authors compare its performance with EXOR and COPE and show that significant improvement in terms of network throughput and number of transmissions can be achieved.

In the INCOR protocol (Zhu et al., 2015), integration of the inter-session NC and OR protocols has been implemented. In particular, the authors proposed a new metric for integration of NC and OR protocol. The analysis presented in this paper employs probabilistic estimation of coding chances into the metric. The INCOR protocol was designed for basic data rate and when a multi-rate scheme is employed this analysis becomes erroneous. This is due to the fact that a link which is a strong link at the base rate, can be a weak/very weak link at the higher data rates. INCOR's performance was compared with the inter-session NC and classic OR protocols, their results indicate that the integrated protocol out-performs either of them. Results have been presented in terms of the transmission count number, and they show that when the link quality is low, the OR protocol has better performance as compared to NC and when the link is strong, NC outperforms the OR protocol. But the integrated protocol outperforms both of the individual protocol as it capitalizes on both of their characteristics. This motivated us to integrate the third element on the network protocol stack, i.e., CP to provide spatial diversity to leverage the broadcast nature of the wireless channel further.

In (Koutsonikolas et al., 2008), the XCOR protocol was designed for single rate network. It integrates the inter-session NC with OR protocols. It is based on the ETX metric (De Couto et al., 2003). It is well known that the ETX metric does not takes into account the multi-rate capability of the network. In (Kim et al., 2012), (Aajami et al., 2012) integration of OR and NC was studied considering the multi-rate capability. The authors concluded that the integration of OR and NC outperforms, the multi-rate NC or the multi-rate OR when considered in isolation.

In (Abdallah, et al., 2015) the authors presented another integration of the intra-session NC with OR protocol. The main drawback of their work is that it is primarily focused on the network throughput alone because packets are transmitted in batches and acknowledgements are done for batches of packets. This is what separates this approach from our work where we encode packets locally and acknowledgements are done for each packet delivery.

In CCACK (cumulative coded acknowledgement) (Koutsonikolas et al., 2011) another integration of the intra-session NC and OR protocols was presented. As opposed to MORE, the authors overcome the challenge of acknowledging the upstream nodes about the reception of coded packets by estimating offline the link delivery probabilities which is based on the ETX metric. CCACK devises a novel mechanism to overcome the losses occurring due to offline estimation as the wireless channels are dynamic in nature. It introduces cumulative coded acknowledgement of the received packets at the forwarding nodes. The authors compared its performance with MORE to show the performance improvements in terms of the network throughput and the number of transmissions. It clearly shows the performance improvement, but it requires complex associated hardware. In MT_NCOR (Lan et.al., 2014) an integration of intra-session NC and OR protocols was implemented. Candidate forwarder set selection and coding/decoding of packets are similar to MORE protocol but the rate control mechanism employed at the source and the forwarding nodes differentiate the MT_NCOR protocol from the MORE protocol. It is designed for fixed data rate, which cannot harness the capacity of the wireless links to the full extent.

In (Qiang et al., 2013) an integration of the inter-session NC and OR protocols was presented resulting in the CoAOR protocol. The authors have presented a new metric for prioritizing the nodes where more coding opportunity arises. A node coding gain formula was presented, which takes into account the number of flows which can be coded together, expected number of those flows which can be decoded at the receiver nodes, and the total number of the neighbors who can decode the coded packets. The authors compared their results with the CORE protocol and showed that CoAOR protocol outperforms CORE protocol. But again their analysis is based on the ETX metrics which is estimated using the control packet from network layer sent at basic data rate and for multi-rate network this metric becomes erroneous.

1.4.2 Integration of NC with CP

In (Manssour et al., 2009) performance of the network coding was evaluated in the presence of an opportunistic relay selection. Based on the results, the authors conjectured that the selection of the relay should take into consideration the coding opportunity which may arise in the relay node. Nevertheless no practical means was proposed for coding opportunity detection.

In (Wang et al., 2014) the NCAC-MAC protocol proposes another integration of the CP and inter-session NC protocols. It does answer an important question of how to cooperate when the direct transmission from the transmitter to the relay node fails. NCAC-MAC supports two forms of cooperation. Namely network coded cooperative retransmission (when there are coding opportunities at the relay node) and the pure cooperative retransmission (when there is no coding opportunity). The performance of the NCAC-MAC protocol is compared with the CSMA and Phoenix (Munari et al., 2009) protocols. NCAC-MAC was designed for single hop network, which is not suitable for WMN. The authors presented comparison of their protocol with CSMA and Phoenix in terms of network throughput, delay, delivery ratio and transmission energy consumption. It clearly shows that the integration of CP and NC is beneficial when the relay nodes are selected based on the coding opportunity.

In the NCCARQ_MAC protocol (Antonopoulos et al., 2013) the authors have performed integration of CP with NC from energy efficiency perspective. Their results also indicate that integrating NC with CP results in performance improvement in terms of throughput as well as delay. This protocol was designed for single hop scenario, where the transmitter and receiver are within the communication range of each other and in between them there are some helper nodes. The authors presented results in terms of the network throughput and energy efficiency. An analytical model for energy efficiency was presented and was validated with simulation results. This protocol is not suitable for wireless mesh network where we need to have multi-hop forwarding.

1.4.3 Integration of NC and Opportunistic forwarding

The BEND protocol (Zhang et al., 2010) integrated the network coding and opportunistic forwarding. The opportunistic coding has been introduced into the network protocol stack. There was no mechanism introduced to combat the fading which is inherent in the wireless channels. BEND was designed for fixed data rate transmission; whereas data rate selection mechanism is non-trivial for performance of the network (Kumar et al., 2010). BEND makes minimal assumption about the routing protocols.

In (Kafaie et al., 2015), the authors propose the FlexONC that includes a mechanism for forwarding coded packets even when the recipients are not the intended receiver. In this work the authors have considered a two-ray model and only base data rate was employed for data forwarding mechanism. A detailed analysis of how this protocol performs on multi-rate network was missing. This work is mainly focused on the MAC layer, assuming a minimal change in the routing protocol.

1.4.4 Routing metrics for Integration

The MORE protocol (Chachulski et al., 2007) employs the ETX (expected transmission count) as the routing metric to compute the distance between a node and the final destination. The CORE protocol (Yan et al., 2010), employs geo-distance as the primary metric for forwarder selection. In order to estimate the local coding opportunities, it employs opportunistic listening and broadcast of the reception reports. INCOR presents coding-based expected transmission count (CETX) to determine priority of the forwarders in a group. It computes the expected number of transmissions required to deliver one packet when the inter-session NC is employed. XCOR employs ETX as the routing metric. CCACK (Koutsonikolas et.al., 2011) presents their integration based on the ETX metrics.

CoAOR (Qiang et.al., 2013) integration employs the ETX metrics for forwarder node selection. Also a node coding gain formula was presented that takes into account the number of flows which can be coded together, expected number of those flows which can be decoded at the receiver nodes and the total number of the neighbors who can decode the coded packets. Based on these two separate metrics the integration was performed. It assumes that the link delivery probability is 1 when the distance between the sender and receiver is less than 100m and 0 when the distance is larger than 200m while between 100m and 200m the link delivery probability is between (0, 1). These are quite simple assumptions that can make the results erroneous when employed in real world scenario. MT_NCOR (Lan et.al., 2014) also employs ETX as the routing metrics. NCCARQ-MAC (Antonopoulos et al., 2013) was evaluated where sender and the receiver nodes were within the transmission range and there were some relay nodes for aiding the transmission. Multi-rate transmission was employed where the transmission was limited to 6, 24 and 54 Mbps from the source and relay transmission was limited to only 54Mbps. BEND (Zhang et al., 2010) uses minimal assumption about the routing protocol, without explicitly mentioning which routing protocol to employ, and there was no new metric mentioned in that work. FlexONC (Kafaie et al., 2015) is an improved version of the BEND protocol where the non-intended receivers of the coded packets may also forward the packets towards the destination.

1.4.5 Multi-rate capability for Integration

BEND, MORE, FlexONC, CORE, INCOR and CCACK employ fixed data rate. In NCAC-MAC, three data rates were employed, 11, 5.5 and 2Mbps, and the data rate was set depending on the distance between the sender and receiver. NCCARQ_MAC employs only three data rates which do not necessarily capture the multi-rate capability of the wireless networks. It should be emphasized that in order to fully capitalize the network capacity, employing multi-rate transmission is non-trivial. The rate selection mechanism plays a crucial role and can use the link SNR based protocol that can be source or receiver initiated. The main difference between the state of the art protocols and the work presented in this dissertation is in the way the data transmission rate is being selected.

1.4.6 Cross layer based Integration

In (Garrido, et.al., 2015) the authors presented a cross layer based integration of the intra-session NC and OR protocols. It employs Hidden Markov Process (HMP) based channel model which creates bursty behavior of the wireless channel for indoor environment. The authors employ the cross layer approach to use the channel information (link quality) to prioritize the nodes who can forward the packets but this link quality estimation is based on the bit error rates which were estimated using the fixed data rates. In (Zhang, et.al. 2016) the TCPFender protocol is presented that introduces a cross layer mechanism for integration of the intra-session NC and OR protocols to cope with the TCP transmissions. As in the OR protocol, the data packets do not necessarily arrive in the same order as they are injected into the network. This causes throughput degradation for TCP transmissions. TCPFender introduces a shim above the network layer to increase the contention window sizes for TCP and to cope with the issues caused by the OR protocols. As MORE, TCPFender considers only the basic data rate for testing their protocol. In (Gómez, et.al., 2014) the authors presented a similar approach to the one used in TCPFender, where they introduced Random Linear Network Coding (RLNC) above the network and below TCP layer. Their mechanism was evaluated for fixed data rate. The main difference between their work and MORE is that TCPFende promotes creating linear combinations of packets starting at the source node in a shim between the network and TCP layers.

1.4.7 Implementation Issues for Integration

The MORE protocol requires a complex hardware to implement the integration of intra-session NC and OR protocols but it does not address the ordering of the TCP packets. Moreover MORE has coding overhead, memory overhead and header overhead. The CORE protocol assumes that the devices have no limitation of power and processing capabilities. The CORE protocol has non-linear time complexity. The time complexity for the INCOR protocol is same as for the Dijkstra’s algorithm. The opportunistic listening approaches employed by the COPE and INCOR protocols are similar and both of them make periodic broadcasts of the packets information, which were received or overheard, even if piggy backed with the data packets, which is certainly an overhead.

The XCOR protocol prioritizes the flows which are heavily loaded to hasten the search for the coding partner selection for network coding operations. It also uses reception report, as in

COPE protocol, to broadcast the information of the packets received or overheard by a node. The MT_NCOR protocol employs the intra-session NC and in order code faster it maintains a pre-calculated table for addition, multiplication and inverse operations that consumes system memory. The CCACK protocol has 24% more overhead than the MORE protocol, which limits the throughput to 35Mbps. The CoAOR protocol employs periodic broadcast of the reception reports and opportunistic listening, as is done in the COPE protocol. It selects the coding partner based on a heuristics that first selects K packets from the output queue and then only searches its partners from packets for different flows that makes the process faster than COPE.

In the NCAC-MAC protocol, the relay nodes are selected reactively, as all the relay nodes who have received the packet correctly contend for the channel to send the packet. In order to ensure that the duplicated transmission does not happen, it employs three contention periods: inter-group contention, intra-group contention and re-contention. This three step contention requires extra signaling, which penalizes the network throughput and makes their protocol sub-optimal. Aside from that NCAC-MAC implements MIMO_NC with the network coding/decoding at the physical layer, which is quite difficult to implement. For the coding opportunity detection NCAC-MAC employs a connectivity table where a node can decide, before network coding, whether the recipient nodes can successfully decode the desired packets. The NCCARQ_MAC protocol was meant to study integration of the CP and NC mechanisms from energy efficiency perspective. In order to evaluate its performance, a set of rules were evaluated without any test bed or any packet-level simulator. In the event the direct transmission is failed from the source to the destination, the destination sends a special control packet RFC (request for cooperation), which can be send standalone or piggy backed with data packet if the destination node has packet for the source node. When overhearing this RFC, the relay nodes can network code packets from source and destination and broadcast them in a single transmission.

The BEND and FlexONC protocols implement the coding search procedure that is quite different from the COPE's procedure for searching and matching the coding partners (packets). It maintains at each node four different queues: queue for control packets, queue for un-coded packet, queue for packet which can be coded together and queue for un-coded overheard packets. Its time complexities are linear to the length of the queue and with the speed of the mobile devices it can be easily implemented without any loss of performance. Our implementation follows a similar approach as BEND and FlexONC, where each node possesses only three queues, without the queues for overheard packets.

Table 1.1 summarizes the comparison of the integration proposed in this thesis with the state-of-the-art.

Table 1.1: Comparison of the proposed integration with the state-of-the-art

Protocol Name	**Mechanisms Integrated**	**Difference with our work**
MORE[2007, ACM]	NC + OR	SD missing; Creates flooding in the network
CORE[2010, IEEE]	NC + OR	SD missing; it's based on link state routing.
NC in the presence of opportunistic relay selection[2009, ICC]	NC + SD	OR missing; How to select coding opportunity are relay was missing; It was a conjecture.
NC_BEND[2010, Computer Networks]	Opportunistic coding+ Opportunistic forwarding	SD missing; No metric for routing packets; Makes minimal assumption about the network layer. Single data rate.
NCAC_MAC[2014, IEEE Trans]	NC + SD	OR missing; It is not suitable for multi-hop scenario; Applicable for single rate networks.
INCOR[2015, ICC]	NC + OR	Basic data rate; does not take advantage of multi-rate capability of the network.
NCCARQ_MAC[2013, Elseviewer]	NC + SD	Single hop scenario; Does not talk about the data rate; Routing functions mission
XCOR[08, ACM Proc]	NC+OR	SD missing; routing is coding oblivious.
Integration of NC and OR [15, ICC]	NC+OR	SD missing
CCACK[2011, IEEE]	NC + OR	SD missing, Based on ETX metric
MT_NCOR[2014, IEEE]	NC + OR	SD missing,
CoAOR[2013, IEEE]	NC + OR	SD missing
Cross Layer based Integration [2014, IFIP]	NC + OR	SD missing
Cross Layer based Integration[2015, IEEE]	NC+ OR	SD missing
TCPFender, Cross Layer based Integration [2016, PeerJ, Computer Science]	NC+ OR	SD missing

CHAPTER 2

INTEGRATED PROTOCOL DESIGN

Introduction

This chapter discusses the design of the integrated protocol for WMN. First each of the three mechanisms (NC, CP and OR) is illustrated with small example. Then the link creation at the MAC layer protocol followed by coding and data rate aware routing (CDARM) metric are detailed. Based on the CDARM metric and link creation at MAC layer mechanism, the proposed method for integration of the three mechanisms is presented. The chapter concludes with the assumption made for the implementation as well as evaluation of the network performance. The proposed integrated protocol stack is based on the IEEE 802.11a based MAC protocol where DCF mechanism is employed for the contention. First, we describe the elements of the integration and then the integrated protocols functioning in the following sections.

2.1 Basic Building Blocks

In the following, the considered implementation of each mechanism is presented first, and then the integrated protocol stack is described. For illustrations, a simple four node network topology is used, as shown in Figures 2.1 and 2.5, where nodes A and B exchange packets and nodes R1, R2 are the relay nodes used to improve network performance.

2.1.1 NC Protocol

NC mechanism is illustrated in Figure 2.1. In this case, nodes A and B have packets for each other; since they are unable to communicate directly, they use an intermediate node R1 for packet forwarding. In case traditional packet forwarding is applied, in order to exchange of two packets, one from A to B and one from B to A, requires 4 time slots (2 slots per packet).

Further, when network coding is applied the two packets are coded into one at R1 and then the coded packet is broadcast to A and B at the same time allowing the destination nodes A and B to decode packets (by storing the packets which was sent by A and B earlier they can decode the desired packet). Therefore only 3 time slots (1.5 slots per packet) are used. The saved one time slot is coding gain.

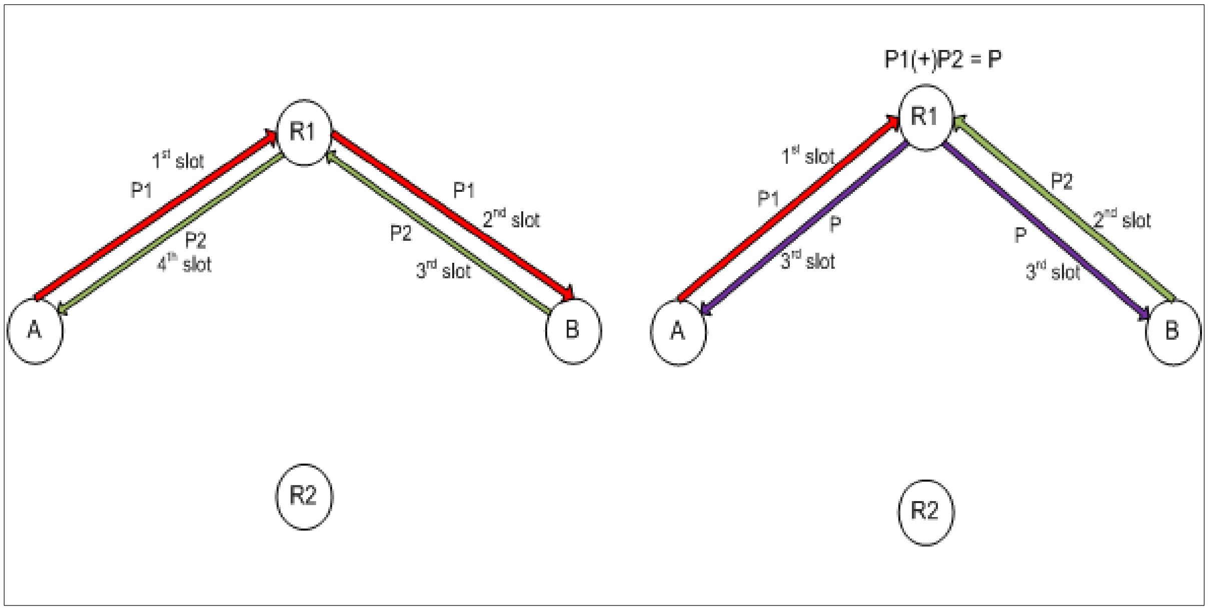


Figure2.1 Illustrations of Network coding

2.1.2 CP Protocol

In this case, Nodes A and B are in direct communication range. Node A has packet P1 for B and it also selects node R1 as the relay node according to the relay node selection criteria (Lin et al., 2009) (the spectral efficiency criteria). The packet is forwarded with the data rate appropriate to the current channel state between A->B. If the direct transmission is successful, node B sends ACK back to node A. The relay node does not intervene in this case as illustrated in the timing diagram from figure 2.2. If the direct transmission is unsuccessful, there is no ACK sent by B, so the relay node forwards the packet after the SIFS (short inter-frame space) + Ack_Timeout period as illustrated in the timing diagram from figure 2.3. Combining two copies of the received packet at node B yields diversity gain that increases the likelihood of correct reception. There can be more relay nodes to aid in the communication but selecting the best relay is sufficient to achieve diversity multiplexing tradeoff as that of multi-relay cooperation (Zhuang et al., 2013). Therefore in this work, we limited consideration to the best relay node.

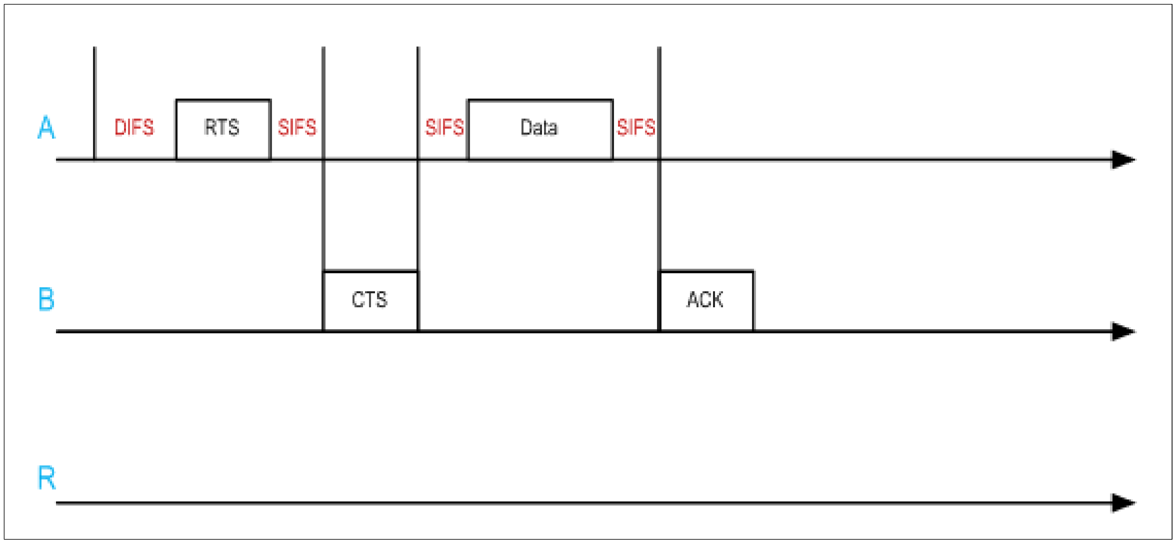


Figure2.2 Timing diagram of Cooperative protocol (direct transmissions)

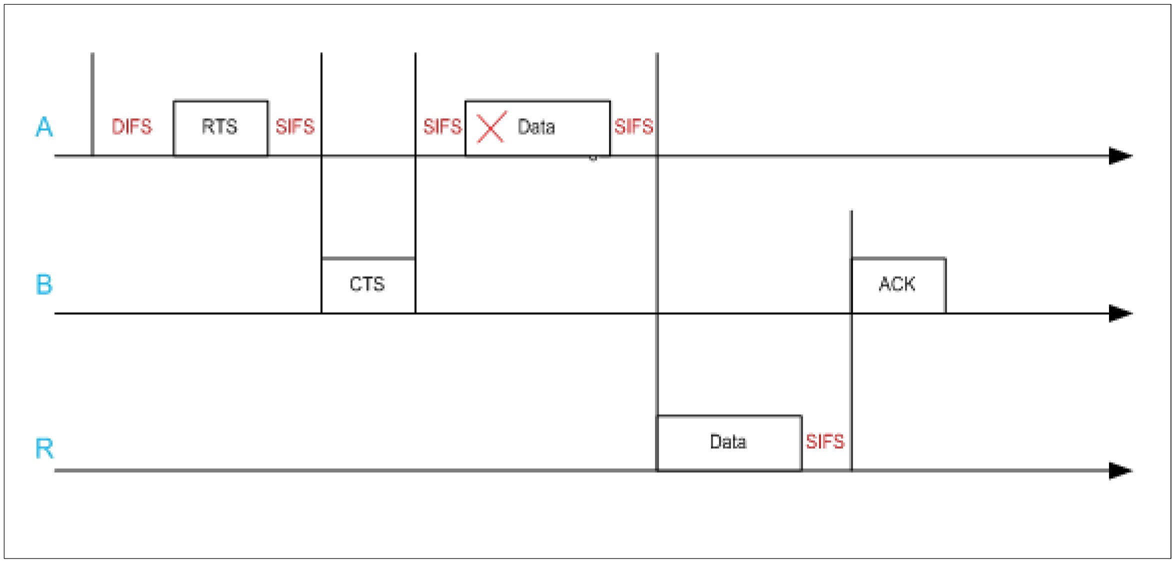


Figure2.3 Timing diagram of Cooperative protocol (relayed transmissions)

2.1.3 OR Protocol

In OR protocol, a node selects a group of next hop forwarders that are closer to the destination than the node itself. The selection is based on a metric. Coordination among next hop forwarders to eliminate duplicate transmissions is an issue that has been dealt via some organized packet exchanges (Boukerche et al., 2014).

Figure 2.4 illustrates a classification of OR protocols based on the type of coordination as described in (Boukerche et al., 2014). In RTS/CTS based coordination, before sending the data packet, a node sends RTS to the group of neighboring nodes, where the node ID-s are ordered based on the priority according to a metric. If the highest priority node receives the sent RTS, it sends back CTS packet after SIFS period. After overhearing this RTS/CTS exchange, the remaining nodes in the group turn on their NAV (network allocation vector) and the forwarding link is established with the highest priority node. If the highest priority node does not send CTS, the second node in the group sends CTS after a 2*SIFS period and so on. We have employed a similar approach between the sender, receiver and relay node, by creating relay links at the MAC layer as explained in the following paragraph.

2.2 Link Creation at MAC Layer (CP_RL)

Suppose node A has a packet to send to node B and network layer selects to cooperate with node R1. Then node A sends RTS with the highest priority for node B and second priority for node R1. If B receives RTS successfully it replies with CTS, after the successful exchange of these handshake control packets, node A sends a packet to B. When the relay node receives RTS, it checks whether it is an intended receiver/relay node, and when it learns it is a relay, it turns on a timer. If the relay node does not hear CTS back from the receiver B, it sends CTS to the sender node A, after SIFS + CTS_timeout period.

If the RTS packet is received successfully at node B, but the CTS packet is received in error at node A, node R1 notices this because there is no transmission from A to B after certain duration. Otherwise, if the CTS packet was received successfully at the relay node, it sends CTS packet back to node A and the communication is established between node A and node

R, this creates the relay links A-R1 and R1-B at the MAC layer. After successfully receiving the packet at R1, it opportunistically forwards the packet to the next hop node B along the route. So, the next hop as fixed by the network layer is changed at the MAC layer and the link creation at the MAC layer bypasses the broken link. This is independent of the Network layer. This is the form of opportunism which was introduced onto the network protocol stack for the purpose of integration (In the traditional protocol when a node sends RTS to a receiver, if the handshake is not successful between the source and the receiver, then the source node assumes that there is a collision as there is no mechanism to separate between transmission failure due to erroneous reception or due to collision. The source node doubles the contention window and waits for that doubled CW + DIFS amount of time before sending RTS packet again to the receiver node. It does not take advantage of whether there was any other node with which link can be established which is closer to the destination than itself. In the integrated protocol this is capitalized when the source node fails to establish a direct link in A->{R1}->B, it establishes links as A->R1 and R1->B in opportunistic fashion).

We have employed the AODV (Ad hoc On-Demand Distance Vector) routing protocol, that is why the relay node can forward packets to L_D, there are other options which can be implemented to change the route completely towards the destination from the relay node, if a link-state routing protocol is employed, since in the link-state routing protocol every node is aware of the other nodes and has route to any destination available. Another option which can be implemented is that if we store the 2NH (next hop's next hop) as suggested in (Zhang et al., 2010), then the relay node may choose to select the 2NH node as next hop or any other node which has a link-to the 2NH node along the route. To minimize the complexity, we have chosen to employ opportunistic forwarding from the relay node to the next-hop.

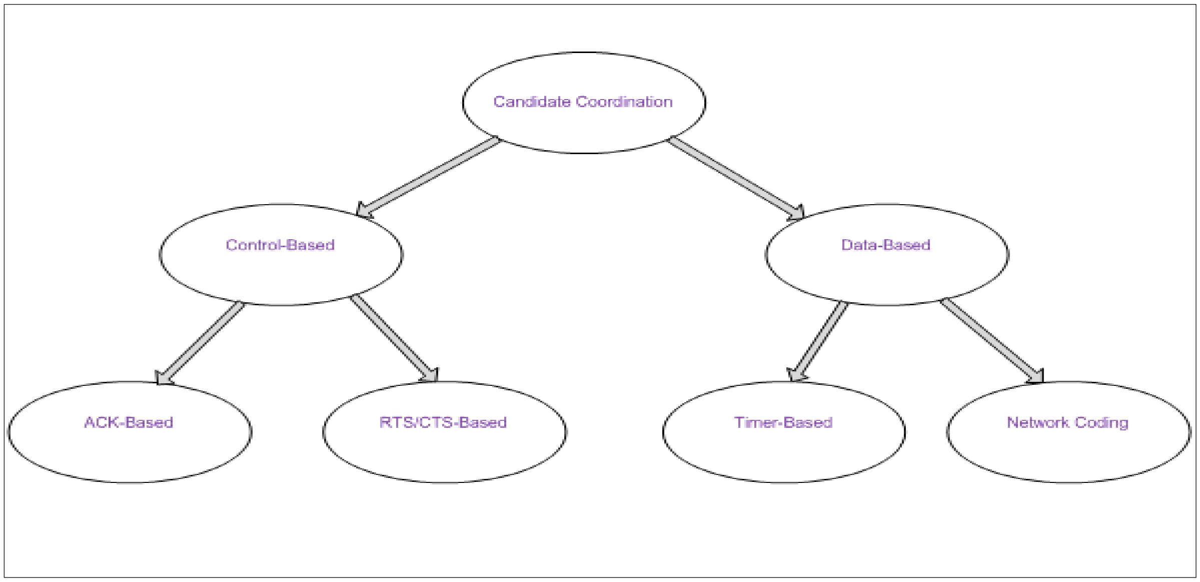


Figure2.4 Classifications of OR protocols based on Candidate coordination

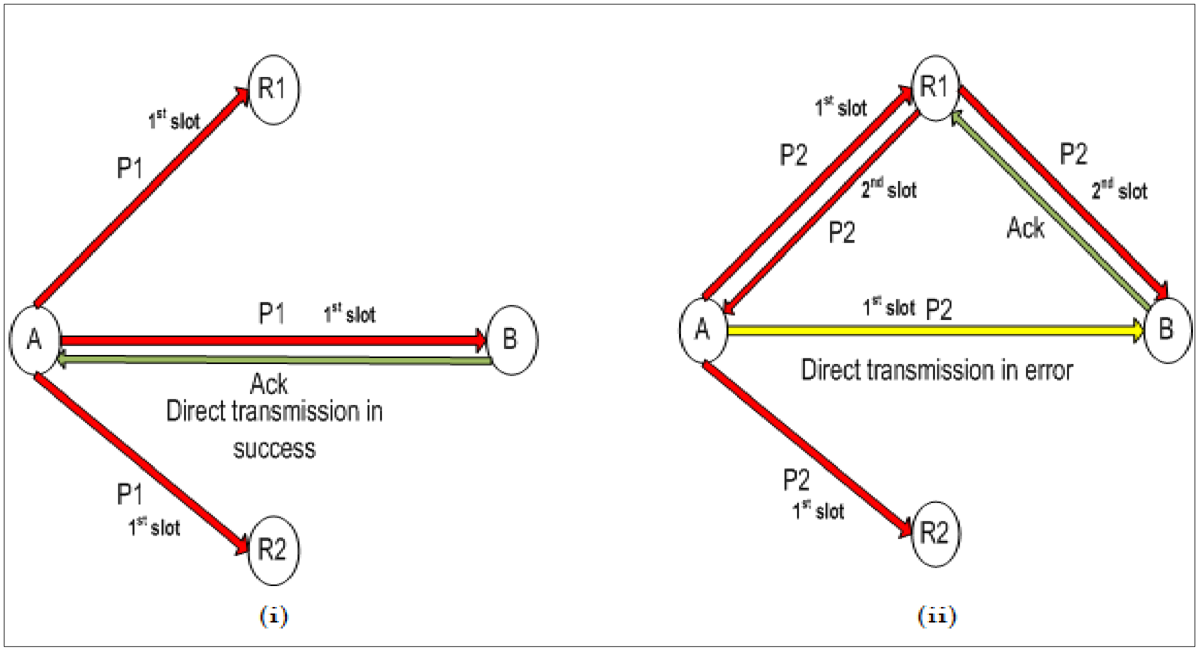


Figure2.5 Illustrations of Cooperative protocol in Integration

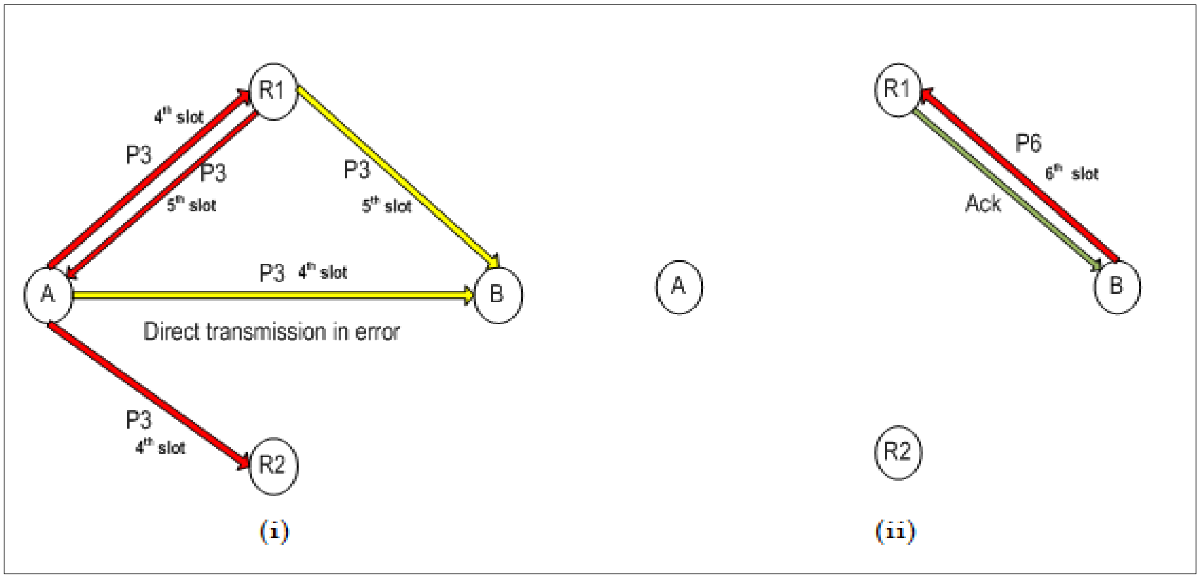


Figure2.6 Illustrations of Cooperative protocol in Integration (relay intervention)

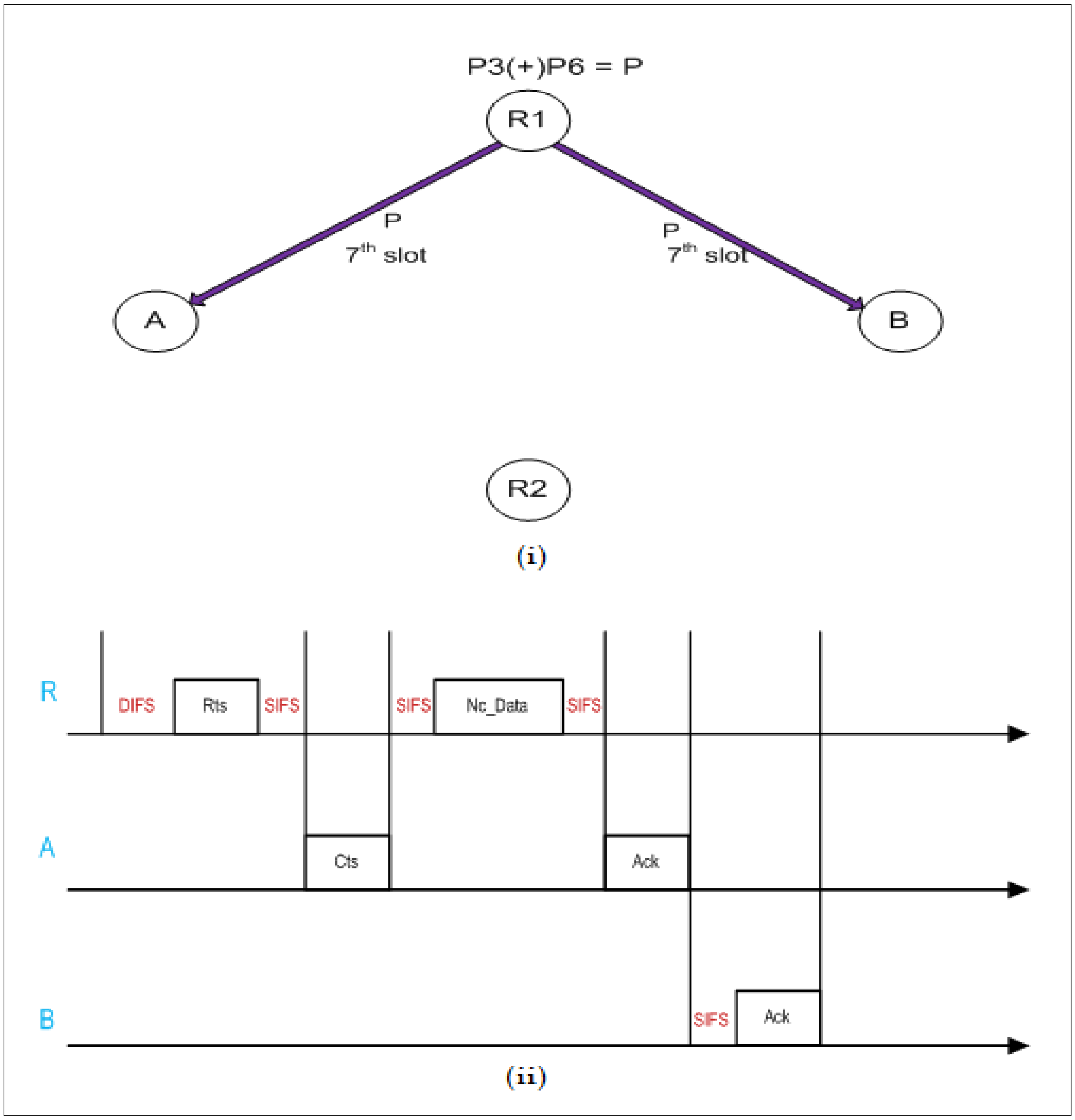
2.3 Integrated Protocol Functioning

Let us explain the integrated protocol using the same network topology example that was used for illustration of each mechanism. Suppose there is a direct link from A and B and a relay node R1 to assist in the communication. Also suppose that there is a link from B to A that also selects R1 to be the relay node. Node A has 5 packets (P1, P2, P3, P4, P5) addressed to B and node B has 5 packets (P6, P7, P8, P9, P10) addressed to A. P1 is sent from A to B and if direct transmission succeeds, the relay node does not intervene, see Figure 2.5 (i).

For P2, see Figure 2.5 (ii), the direct transmission is not successful, so the packet is relayed by R1 in the second slot. After receiving the second copy of P2, the two copies of the received packet are combined at node B and decoded successfully. Then node B sends ACK to the relay node. Note that after the relay node transmission, node A knows that packet P2 was forwarded by the relay node, when the relay node forwards the copy of P2, the node A checks P2’s unique sequence number with the packet which is in its repository, when it learns that this is the same packet which was sent by A and the its being forwarded by the relay node, it discards this packet because it has already reached one of the nodes along the route (which is relay node here). We refer to this packet transfer as CP transfer.

For P3, see Figure 2.6(i), the direct transmission is not successful, so the packet is relayed through the relay node in the next slot. After receiving the second copy of P3 by node B, the two copies are combined (two copies arriving through two different paths experiences different level of fading), but the decoding is unsuccessful so node B does not send ACK. Note that after the relay node transmission, node A knows that packet P3 was forwarded by the relay node, so it moves to the treatment of the next packet. Since the relay node did not receive any ACK from the receiver node B, it forwards (sends) P3 to the network layer to resolve route to the final destination and determines the next hop node, which could also be node B. We refer to this transfer as OR transfer since it opportunistically changes the previously established route.

In order to illustrate network coding integration, we assume that node R1 selected node B as the next hop node for P3 and that in the next slot (6th) node B gains the channel and sends RTS to node A, but the RTS packet is not received by A. Then after the timeout period R1 sends CTS packet back to B, and a link is established between B-R1 and node B transfers packet P6 to R1, see Figure 3.6(ii). Note that this transfer also falls into the OR transfer category. Then node R1 notices that it can code together packet P3 with P6, and sends the coded packet to A and B in a single slot as shown in Figure 2.7(i) and 2.7(ii).



(i)

(ii)

Figure2.7 Illustrations of Network coding in Integration

2.4 Node-Link Metric

Our integration approach is based on a node-link metric, coding opportunity and data rate aware routing metric (CDARM). This metric is used to select a route towards the destination and the potential relay nodes. Apart from the link data rate, it takes into account coding opportunities as well as opportunities for cooperation. As mentioned earlier, the integration of the three mechanisms is based on the coding opportunity and data rate aware routing metric as well as the link creation at the MAC layer. The CDARM metric helps to select relay node with coding possibility as well as opportunity to cooperate. The metric for link A-B is given as follows:

$$CDARM(A-B) = \frac{1+ Modified\ Interference\ Queue\ Length(A)}{Link\ Data\ Rate(A-B)} \qquad (2.1)$$

2.4.1 Modified Queue length

First the modified queue length is measured for within a node, for example say there are three flows F1(f1), F2(f2) and F3(f3) passing through a node. If flow F1 and F2 can be coded together, then their contribution in the queue is counted as max (f1, f2) + f3, where f1, f2 and f3 are the numbers of packets from flow F1, F2 and F3 respectively. Since F1 and F2 can be coded together, so their contribution in the queue is max (f1, f2).

$$MQ(A) = \max(f1, f2) + f3 \qquad (2.2)$$

2.4.2 Modified interference Queue length

The modified queue length is not sufficient to measure the traffic load in a network as a node who may have few packets, but when it is surrounded by other nodes, it will still face congestion because the nature of the channel is shared. In order to take into account the traffic and interference, modified Interference Queue (MIQ) has been proposed in (Le et al., 2008), it accounts the modified queue length of its own as well as all of the neighboring nodes which are within the interference region.

$$MIQ(A) = MQ(A) + \sum_{i=1}^{n} MQ(i) \qquad (2.3)$$

Where *MQ (i)* refers to the interfering node *i*.
And link data rate has been estimated as

$$Data\ Rate(A-B) = BW * log2(1 + SNR(A-B)) \tag{2.4}$$

BW is link bandwidth.
Cost using R1 and R2 as relay node is defined as

$$L1 = CDARM(A-R1) + CDARM(R1-B) \tag{2.5}$$

$$L2 = CDARM(A-R2) + CDARM(R2-B) \tag{2.6}$$

The path which has least cost is chosen for relay selection as

$$Min\ (L1, L2)$$

Say for example L1 results in a minimum-cost. Then the algorithm checks if using this relay node is beneficial or not according to the following criterion. If the following condition is satisfied, using relay node is beneficial.

$$CDARM(A-B) > 0.5(CDARM(A-R1) + CDARM(R1-B)) \tag{2.7}$$

The 0.5 factor in the equation accounts for two transmissions, first from by sender node to relay node and then by relay node to the receiver node. The numerator of the metric in (2.1) is associated with the node and the denominator is associated with the link. In this way, the node metric as well as the link metric are combined. Relay node was selected according to the spectral efficiency as well as coding opportunity based criteria. While selecting the relay node, the questions posed for selecting the relay node (Zhuang et al., 2013) for cooperative protocols have been taken into consideration: who to cooperate with? The best relay node among a set of potential relay nodes has been selected. How to cooperate? Pro-active cooperation have been employed for cooperation. And when to cooperate? Cooperation was triggered only when it is necessary, i.e., in an incremental fashion, as unnecessary cooperation sabotages the gain from cooperative protocol (Zhuang et al., 2013). By selecting neighbor who is strong to support higher data rates which reduce the transmission time thereby improving spectral efficiency. The path selection procedure and the criteria for selection of the path are described in section 3.2.3, RREP phase (Route reply phase).

2.5 Algorithm for MIQ calculation

Suppose five different flows {F1, F2, F3, F4, F5} are going through a node. Figures 2.8 and 2.9 help us describe them. Queue length in first case:

$$MQ1 = T_{f1} + T_{f2} + T_{f3} + T_{f4} + T_{f5} \tag{2.8}$$

On the second case where flow A, B and C can be coded together, the queue length is modified as following:

$$MQ2 = max\,(T_{f1}, T_{f2}, T_{f3}) + T_{f4} + T_{f5} \tag{2.9}$$

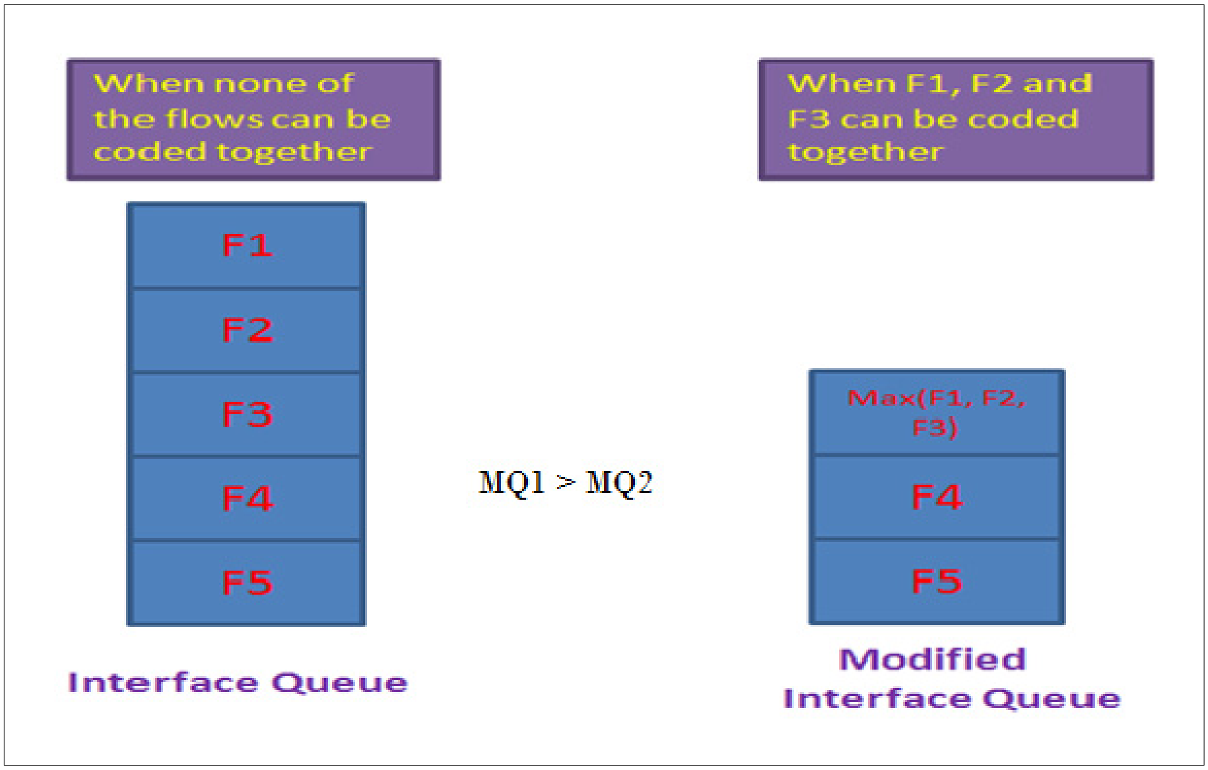


Figure 2.8 Modified Queue Length illustrations

This is the representation how much we can gain if we use that node along the way if the coding opportunity arises and we can tap on to that. In order to estimate the modified queue length undirected graph has been used. Each flow is being represented by vertex associated with the vertex is the number of packets from that flow and the edge between them is a representation of coding possibility.

Bron-Kerbosch algorithm has been used to find all the cliques (completely connected sub-graph) of the graph, and then it was modified to get the Modified Queue length at a node (briefly described at section 2.4.1 and 2.4.2). For details of modified interference queue length calculation please refer to (Le et al., 2008). Alternatively a node can also learn about the coding opportunities by snooping on the communications of the neighbouring nodes.

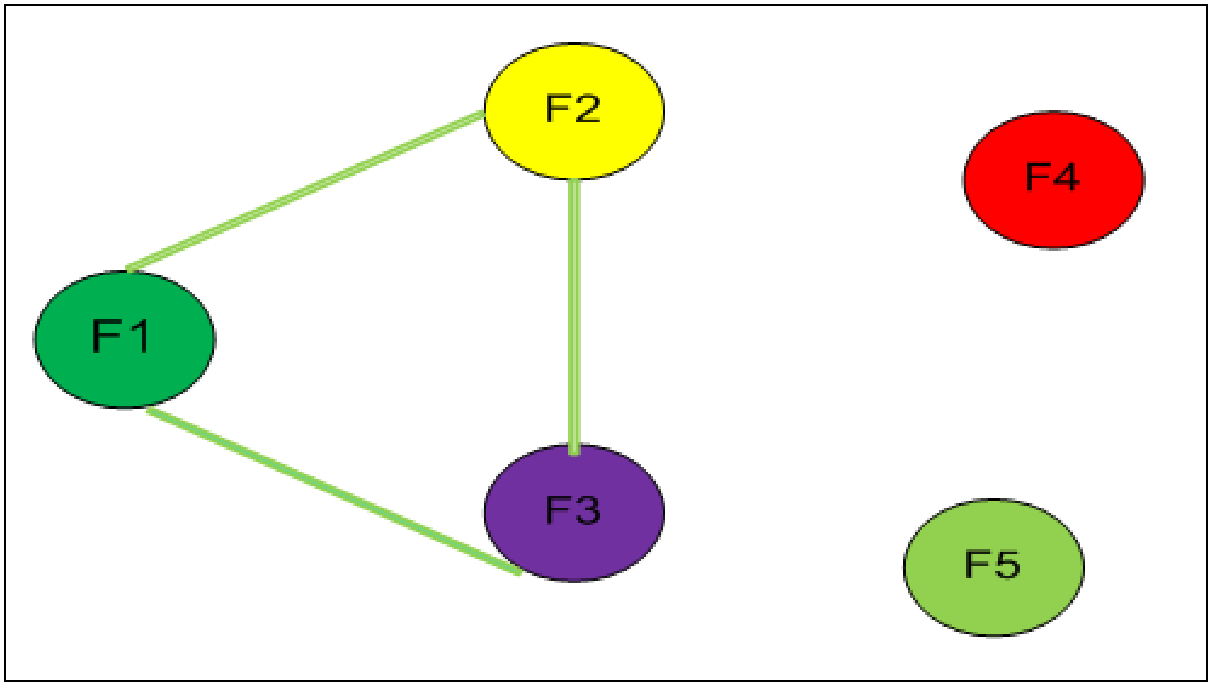


Figure 2.9 Graph representation of the Modified Queue Length

2.6 Assumptions

- All the nodes in the network were assumed to be in promiscuous mode. They can overhear the communications of all node which are its one-hop neighbors;
- Each node knows the link qualities between itself and its one-hop neighbors and the link qualities between neighbor's and its neighbors;
- Each overhearing node stores packet for a certain duration for the purpose of decoding network coded packet. Each transmitter also stores the packets which it has transmitted for a certain interval;
- Each node maintains three different queues, namely control packet queue, native (non coded transmission) packet queue and Q_Mix which stores the packet in a linked list where the packets which satisfy the coding conditions are grouped together;
- The encoding and decoding operations of the network coding are bit-wise XOR;

- The network layer control packets(hello) was allowed to convey the MAC address as well as the link SNR and the modified interference queue(MIQ) length.

Chapter Summary

This chapter describes the methodology employed for integration of the network coding, spatial diversity and opportunistic routing mechanisms for wireless mesh networks. First the basic mechanisms are illustrated with examples, then it presents the CDARM (coding and data rate aware routing metric) and the link creation mechanism at the MAC layer on which the integration approach is based on. Then with help of an example the integration approach has been illustrated. At the end it discusses the assumptions which have been made during the implementation and testing of the integrated protocol stack.

CHAPTER 3

DESIGN AND IMPLEMENTATION DETAILS

Introduction

In the previous chapter, the integration approach has been discussed. In this chapter first the design objectives and challenges are described followed by the modifications which have been carried out at network, MAC and Physical layers of the OSI (open system interconnect) reference architecture. A framework for restraining the route-request (RREQ) packets during the route discovery phase, RREQ phase, route-reply (RREP) phase, opportunism in the routing protocol, cooperation among the MAC and network layer, MAC header modifications to facilitate the integration, enhanced network allocation vector (NAV) update procedure, queuing and coding policy, decoding, acknowledgement, retransmission policy, prioritization of the coded packet transmission, physical layer modifications. Flow charts have been provided to facilitate the reader to grasp the underlying mechanisms and algorithms for integrated protocol stack. At the end the modified network protocol stack is presented.

3.1 Design Objectives and challenges

It is well-known fact that the NC is sensitive to erroneous channel and CP as well as OR protocol results in improvement in performance under lossy channel condition. The main challenge was to bring these gains in a single platform, so that gain from one protocol does not sabotage the gain from other protocols, i.e., to create cohesion in the protocols functioning. In order to design the integrated protocol, the following issues were carefully addressed.

- Selection of relay node for cooperative diversity and improving spectral efficiency, these objectives are detailed in the node-link metric section 2.4.2;
- Employing Opportunistic forwarding: Link creation at the MAC layer as well as

capitalizing on the progress already made by the packet towards the destination;

- Expediting the coded packets transmission: In order to maximize the coding chances coded packets must be prioritized for transmission within a node and among the nodes;
- Duplicate packet suppression: When opportunistic forwarding and network coding are employed, the protocol must ensure that duplicate packets are not transmitted by other nodes along the routes;
- Enhanced NAV update procedure for coping with the cooperative protocol as well as Link creation at MAC layer protocol.

In order to address the above issues to realize the objectives of integration (to improve network throughput and improve reliability), the network architecture has been modified, where additional functionalities (storing neighboring nodes information, coding opportunity based relay selection and a cross layer communication interface at the network layer, then at the MAC layer three interface queues, coding graph, priority based scheduler, network coding and decoding module, overheard packet repository, cross layer communication interface at the MAC, at physical layer a packet buffer, and an equal gain combiner) into the network protocol stack are introduced. In the next section, details of the modified architecture are presented starting with network layer, then MAC layer and the physical layer.

3.2 Network Layer Modifications

For the purpose of integration, AODV routing protocol (Perkins et al., 2003) have been chosen to discover route in an on-demand fashion, DSR (Johnson et al., 2007) was not chosen, as it requires the each packet to carry whole path information. As another option, link-state routing protocol may be used. Concerning the link metrics used in AODV, in the literature they are broadly categorized as topology based and load based metrics. Example of topology based metrics are hop-based, ETX, ETT, etc. and for load based metrics one can mention traffic intensity and interference aware metrics (Karia et al., 2013), (Sheshadri et al., 2014). In our implementation, the applied AODV protocol is based on the node-link metric proposed in Section 2.4.2, which is a combination of the topology based and load based metrics. The advantage of using node- link metrics is that it guides the packets on the path where coding opportunity may arise and also it weighs whether using that path is beneficial or not. A path may be coding possible but using an alternative path is beneficial because of the characteristics of the links along the path.

3.2.1 Restraining the RREQ packets

In conventional AODV protocol, nodes that receives a route request packet, RREQ, for the first time, updates its route back to the source node without judiciously considering whether the link via which the packet came is strong or not. Also in the conventional ETX metric based routing, a node processes the RREQ packet from the origin or the neighboring nodes only if the ETX metric, of the link by which the RREQ packet came, is above or equal to the given threshold. These threshold values are estimated using the number of control packets which are sent at the basic data rate. In this case, when employing multi-rate transmission at the MAC layer for forwarding the data packet, the transmission becomes prone to errors because of the channel dynamics. In order to overcome this difficulty, in our implementation, the link SNR moving average has been employed. Therefore the routing decisions are not solely based on the number of control packets a node receives during a period of time but also on the average link SNR. In this case, the routing criteria can be described as follows:

- Choose paths which met certain criteria only (average link SNR is above a given threshold), to sort out uncompetitive path;
- Then among those paths, choose the path which results in minimum cost path in terms of the CDARM metric.

This strategy allows the nodes to choose only those routes that are strong and stops the flooding of the RREQ packets which can result in network congestion.

3.2.2 RREQ phase

When source node A wants to establish a route to destination node B, it broadcasts the RREQ packet with a destination address and routing information. When a node receives RREQ, it first checks if the link meets the minimum average SNR requirements. If the requirements are met, it checks if it has already processed a request with the same RREQ_ID. If yes, the packet is discarded, otherwise the node estimates the cost to the previous hop node(in terms of the CDARM metrics), and checks the cooperation condition if it is beneficial in terms of the CDARM metric as stated in Node-Link metrics section 2.4.2. If using the relay node is beneficial then it stores the relay node's address when creating the route to the origin (which is reverse route). Then the node checks if it has a route to the destination. If there is no route to the destination, it includes the cost up to itself from the origin. This process has been put in a pictorial format in figure 3.1.

Then it updates info into the RREQ header and broadcast it. The gratuitous reply is allowed (i.e., any node which has a route to the final destination is allowed to reply on behalf of the destination node). Let us define each link l on the path L. Then if the $MIQ(l)$ is the modified interference queue length of the transmitter on l, and data rate on the link R_l, then CDRAM metric of the link as calculated as

$$CDARM_l = \frac{1+MIQ(l)}{R_l} \tag{3.1}$$

For the cost of the entire path can be calculated as

$$CDARM_L = \sum_{i \epsilon L} CDARM_l \tag{3.2}$$

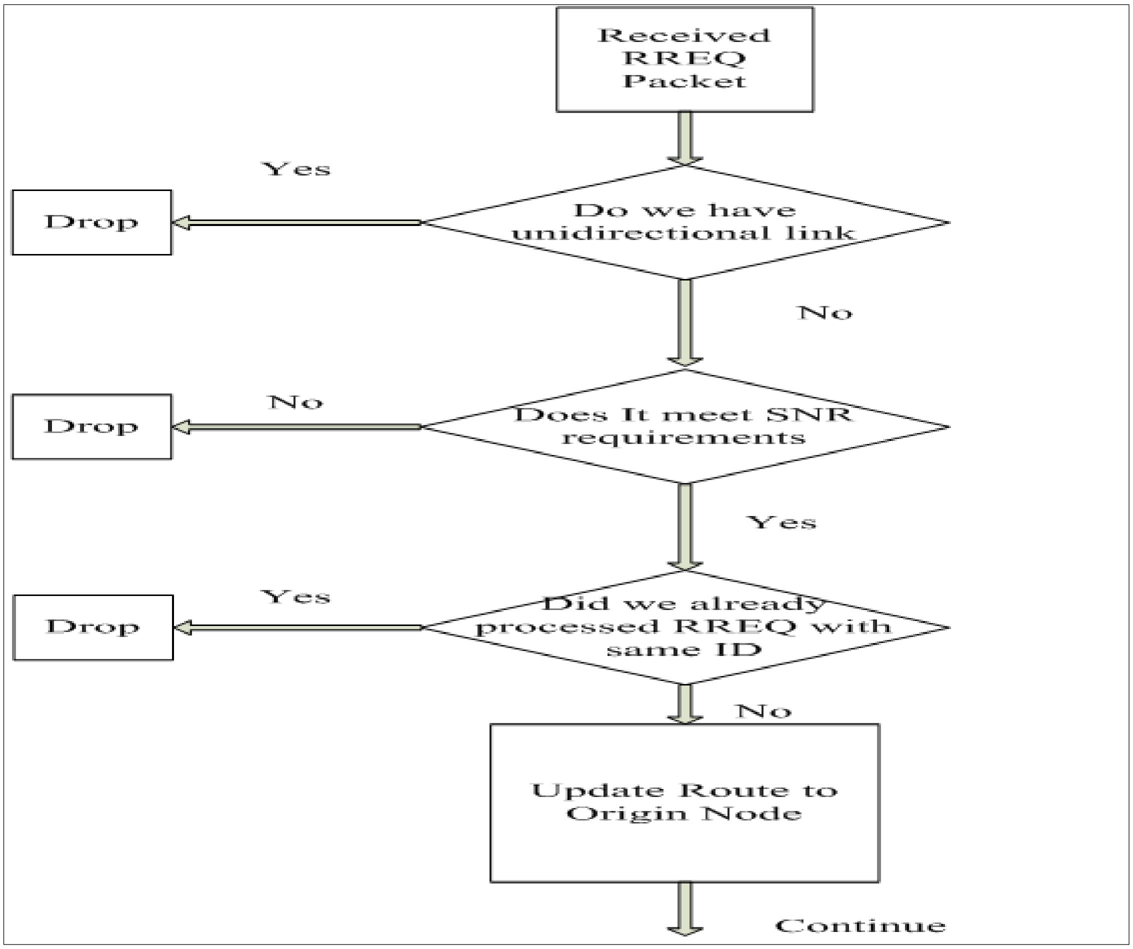


Figure 3.1 Flow chart for RREQ phase

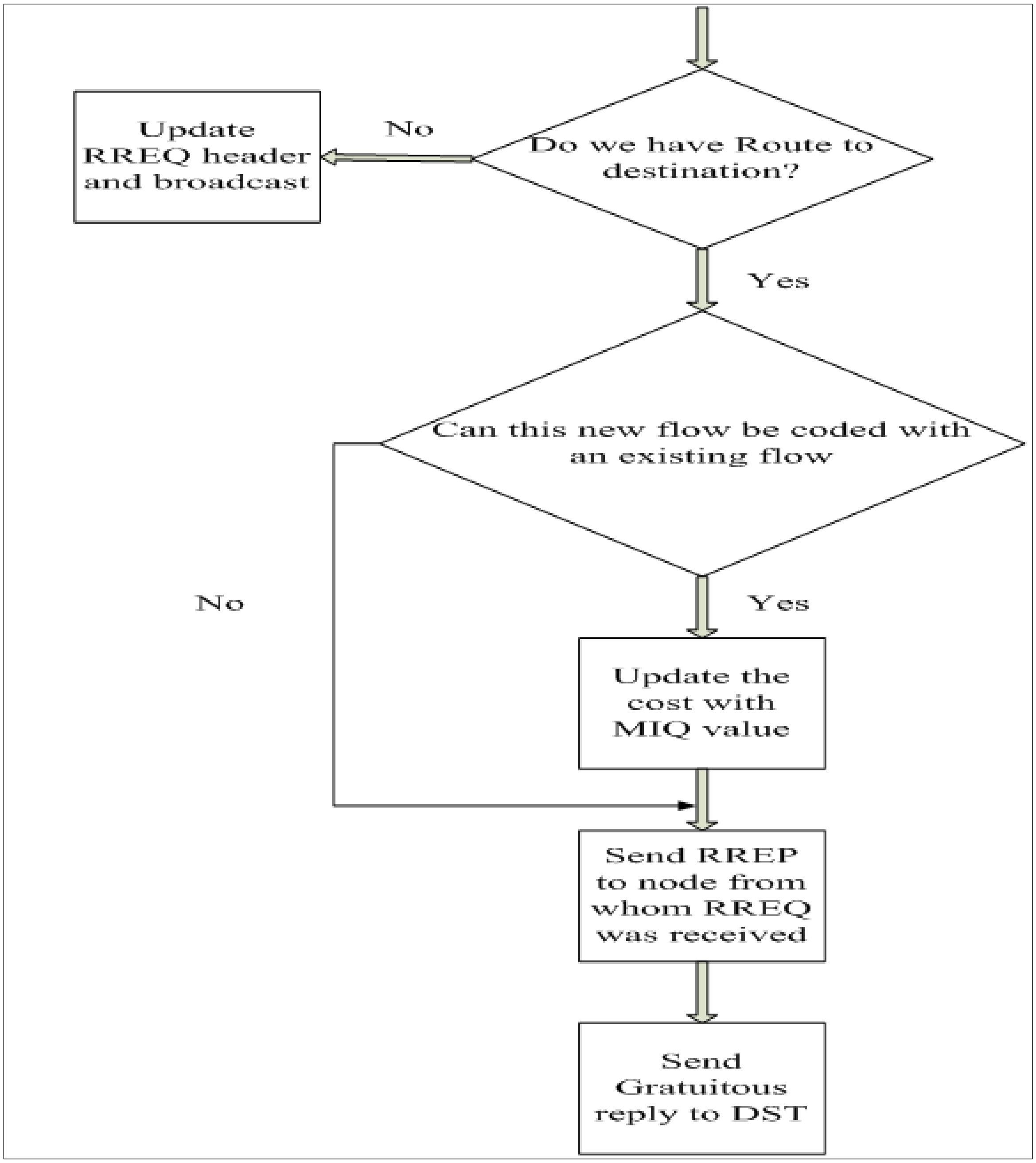


Figure 3.2 Flow Chart for RREQ phase (second half)

3.2.3 RREP phase

When a node notices that it has route to the destination or the RREQ arrives at the destination, then it sends reply back to the node from which it has heard the RREQ. When an intermediate node(an intermediate node is a node which is not final destination) sends the reply back it checks whether this new flow can be coded(by checking the coding conditions mentioned in section 3.5.3 Queuing and Coding Policy) with any other existing flow. If yes, then it recalculates the MIQ value and the node-link metric, and inserts it to the RREP header. Upon receiving RREP any intermediate node learns about the coding opportunities at that node and estimates the cost from which node it has overheard the RREP, and it adds up to the cost. This process continues till the RREP finally arrives at the source node. At the source node, if this is the first RREP for that destination, the routing information for that destination is stored along with its cost and the next-hop information. The source node also checks if there is an opportunity to cooperate with nodes which can be beneficial, according to the relay node selection criteria described in section 2.4.2 (equation 2.7), and then adds the relay nodes address to the routing table for that destination. If the source node receives another RREP for the same destination with smaller cost than the previous route, then it removes the previous route and stores the new one.

3.3 Opportunism in the Routing Protocol

Opportunism is introduced into the routing protocol in the sense a cooperative link is broken down at the MAC layer on real time, which is explained in more details in section 2.1.3, OR protocol, in order to facilitate that the IP header is enhanced to include the next hops IP address. When a link is created at the MAC layer, (as in section 2.2) a new link is established between the sender and the relay node and in that case the packet transfer responsibility is transferred to the relay node; the progress made from the sender to the relay node towards the final destination was capitalized. In this case the relay node forwards the packet to the source nodes next hop, (a transmitter sends a packet, when the direct link fails, relay nodes makes the transmission on behalf of the source node. In the event the transmission from the relay node also fails, the packet has already reached the relay node, which is closer to the destination than the source node itself, so we capitalize on that progress) if this relay node deems to cooperate with another node is beneficial, then it does so.

3.4 Cooperation among the MAC and Network Layer

Cooperation among the network and MAC layer is extremely important as they are dependent on each other. In the proposed approach a node learns about its neighbors and the link quality between those nodes and itself as well as the link quality among those nodes by snooping on the channel in promiscuous mode. This information is stored in a data structure at the network layer and the MAC layer successively keeps this data structure updated. In particular this data structure is constructed by snooping on the channel on promiscuous mode and when a packet is exchanged between two neighboring nodes, the listening node learns about the data rate which is used and at the same time the SNR of the received packet at the listening node. Please note that this cooperation does not incur any extra overhead in terms of communicating metadata to the neighbors, as it is done by snooping on the channel in promiscuous mode as well as the exchange of the "HELLO" packet which is used for conveying the metadata to estimate the routing metric. This data structure is used by the network layers to select the strong neighbors as well as for the routing decisions. Also, after the establishment of the route, the MAC layer consults this data structure for selection of the data rate. So there is a two-way communication between the MAC and network layer.

3.5 MAC Layer Modification

The MAC layer modifications are listed in the following.

3.5.1 Header Modifications

In the integrated protocol stack data packets are transmitted in three different modes, namely: network coded mode, cooperative mode (coop-native) and non-cooperative mode (non-coop-native), the data packets which are not coded are referred as native data packets. In order to differentiate between coded, non-coop-native and coop-native packets, the MAC header is enhanced. When a packet is sent in non-coop-native mode, its header is similar to the 802.11 specifications except for the fact that the frame control sub-field is marked as non-coop-native. When a packet is sent in coop-native mode, its RTS, CTS, DATA and ACK header are enhanced as presented in Figure 3.3. The third address RLY represents the relay node with which the transmitting node wishes to cooperate.

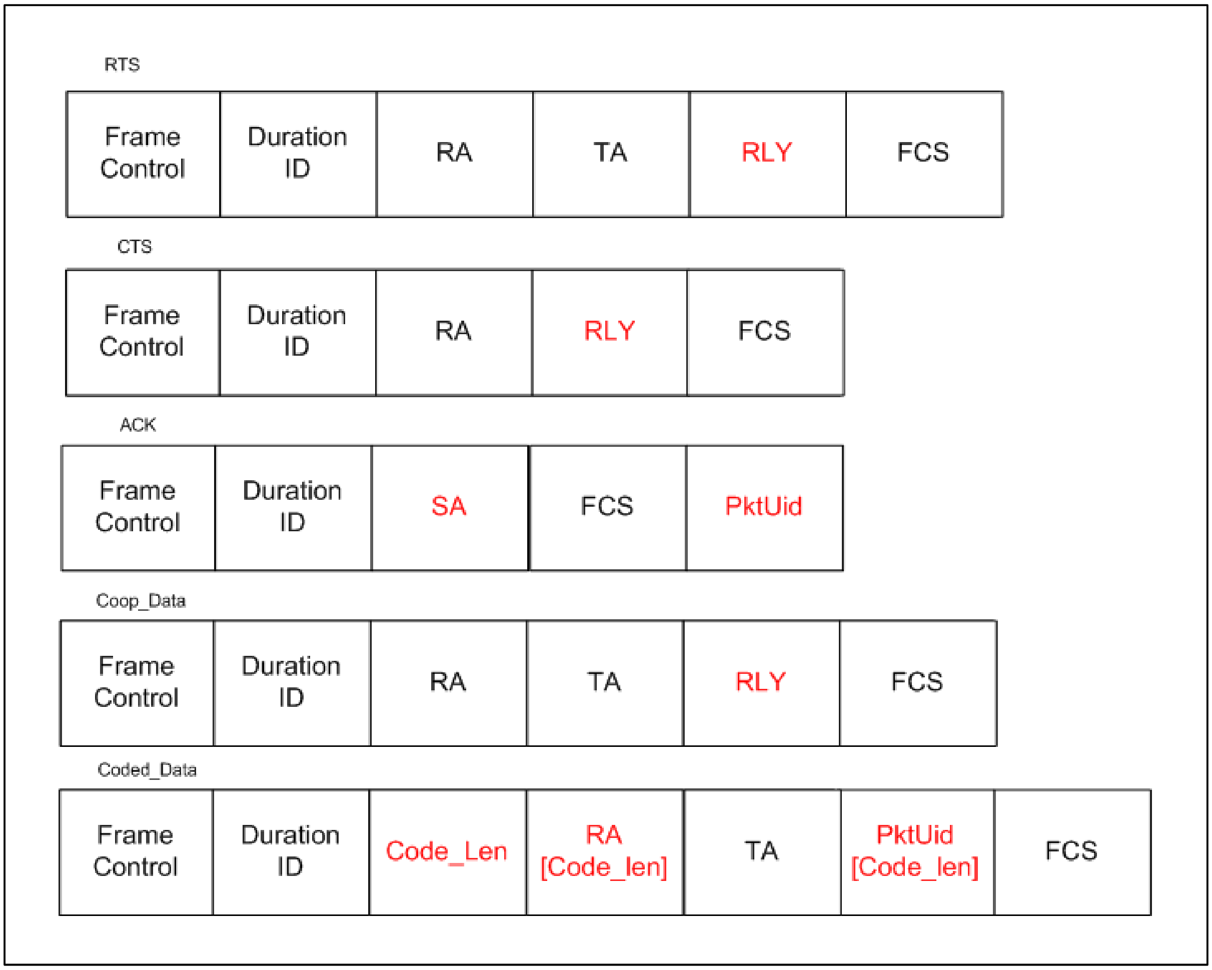


Figure 3.3 Modified MAC headers for Integrated Protocol

When coded packets are sent, the frame control sub-type is marked as coded. There is an array of addresses which are the recipient of the coded packets. Namely, the second address is the sender's address, and we have an array of packet-IDs of the packets which are intended for the nodes whose addresses are included in the array of recipients address, Code_Len represents a number of packets being coded. The ACK packet contains the SA (data packets recipient) instead of RA (data packet sender) and the unique packet ID for which the ACK is for.

3.5.2 Enhanced NAV for Relay Link Creation

Consider cooperative mode for the link is A-{R1}-B. First node A sends RTS packet with the addresses of receiver B and relay node R1. Suppose that the link is not established between A-B but instead the link is established between A-R1. In the 802.11 based Network Allocation Vector (NAV) mechanisms, the other nodes (the nodes which are in the vicinity of the transmitter and the receiver node) lose the chances for transmission even after the successful exchange of data packet. The reason is that when a node sends RTS packet, it includes the duration for which the channel may be occupied with its last known channel condition. In cooperative mode this time can be described as CTS_Timeout + Data_Xmission_Time(A) + SIFS + Data_Xmission_Time(R1) + SIFS + ACK_Timeout (the time which is required to transmit the data which is dependent on the data rate at which it is being sent). Same is true when we employ the cooperative protocol. Even if the direct transmission is successful, the nodes which are in the vicinity of the transmitter and the receiver node, still keeps the NAV on, because the NAV update does not employ a judicious update procedure. In the event the relay link is created at the MAC layer as described in section 2.2 (CP_RL), the data transmission time is halved, which the current NAV fails to take into account. In order to cope with this, the NAV update mechanism has been modified. In the new NAV update procedure, when a node overhears a packet, it checks first for the sender and receiver addresses and the type of the packet. First, say it receives RTS packet, it has access to the sender and receiver's address, so the node knows that a communication is requested for the duration which is stored in the header. It stores the sender and the receivers address. Next, if it overhears CTS within certain duration (CTS time out period), and if the CTS recipient is the same as last RTS sender, then it stores the info also for last CTS sender.

Further, if the next packet is a data packet, between the last heard RTS sender and receiver, then it updates to the duration which is mentioned in the data packets header, instead of comparing it in a traditional fashion. If the data packet is successful, the receiver node sends ACK back to the sender of the data packet, any node in the vicinity who has overheard the RTS/CTS exchange and if it learns that the data packet exchange has been successfully finished then it updates its NAV instead of waiting for it to expire. Again when a node sends

RTS, it requests the channel for the duration which is last known to it between the sender and the receiver. Now, when it comes to the multi-rate protocol, it is not optimized. A simple example will suffice. Suppose node A, sends RTS to node B, according to the last known channel condition it estimates packet length/ (data rate (6mbps)), now after a successful exchange of RTS/CTS it sends data packet at 18mbps according to the current channel condition. So the duration which the channel will be occupied is packet length/ (data rate 18mbps) which is much smaller than what was requested before. If not employed judicious update, the nodes in the vicinity of the RTS/CTS sender and receiver will be quiet for the entire duration. Flow chart for NAV update procedure has been drawn in Figure 3.4 and 3.5.

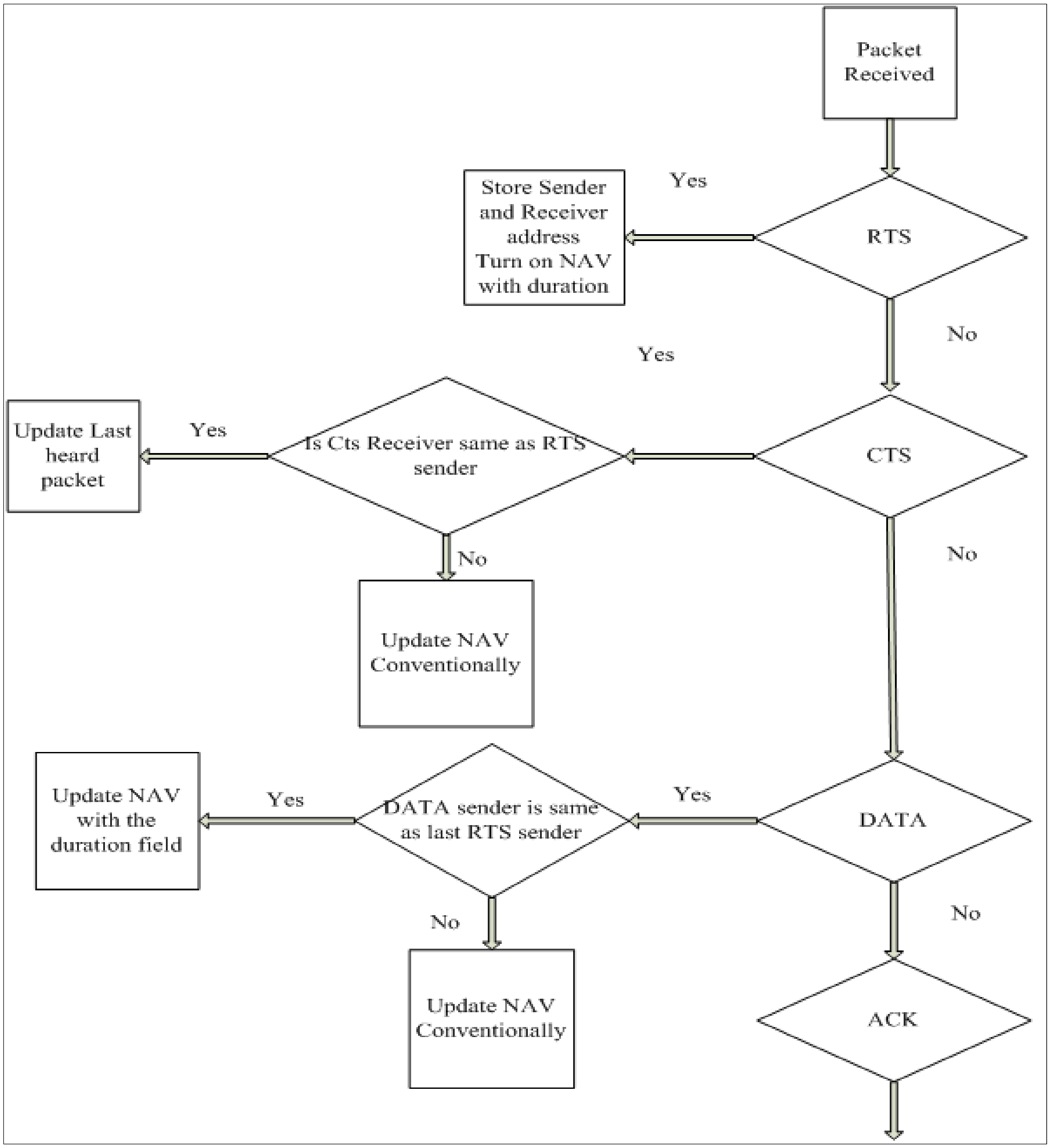


Figure 3.4 NAV update procedure for Integrated Protocol (I)

The rest of the process carried out during the NAV update is depicted at the second part of this figure which is Figure 3.5.

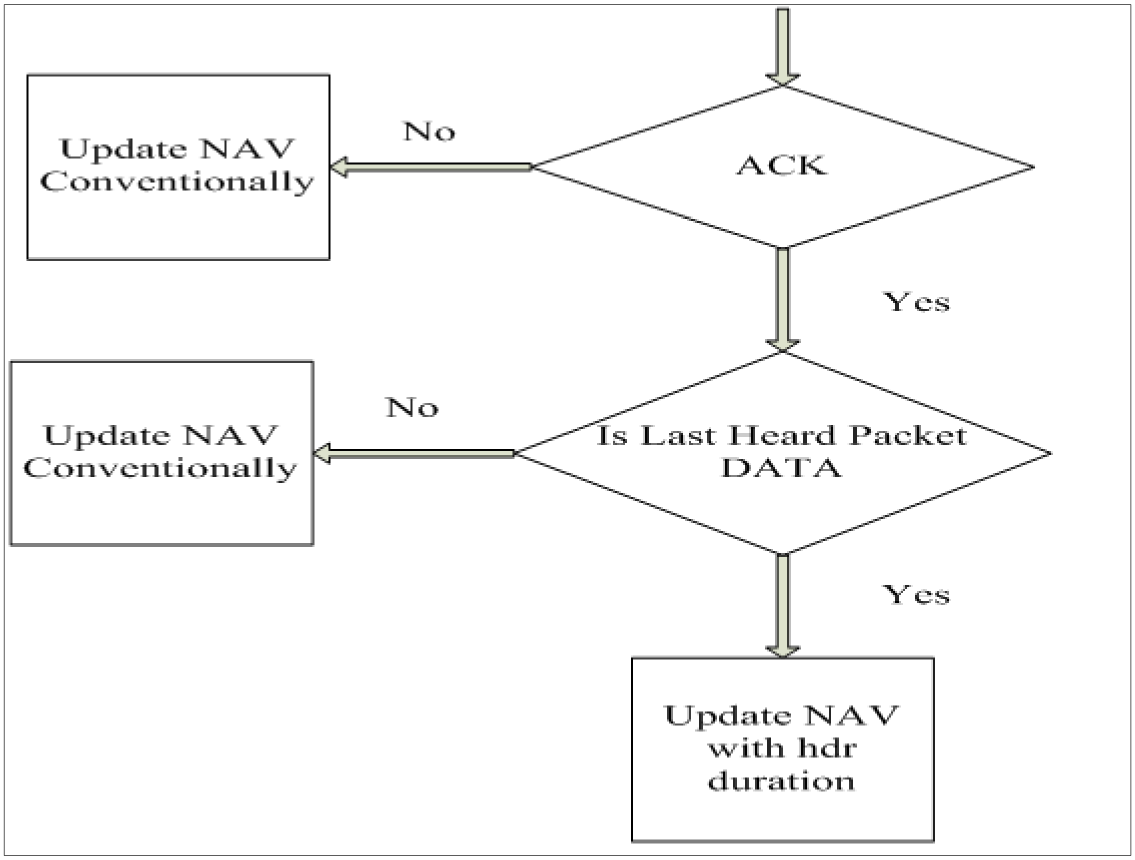


Figure 3.5 NAV update procedure for Integrated Protocol (II)

3.5.3 Queuing and Coding Policy

In the integrated protocol, packets can be coded only at the relay and intermediate nodes along the path. The coding structure has been limited to two hop(local coding and decoding is being employed, if a node receives a coded packet which is meant for it, it must decode to retrieve the original packet which is meant for that node, if it cannot decode the packet it will discard the network coded packet and send NACK(negative ACK) to the transmitter of the coded packet, so that it knows which node could not decode the desired packet and so it schedules that packets as non-coded packet at a later transmission opportunity). Then, the necessary and sufficient conditions for coding two data packets, P1 and P2, together are:

- P1's next hop is P2's previous hop, or P1's next hop is P2's previous hop’s direct neighbor;

- P2's next hop is P1's previous hop, or P2's next hop is P1's previous hop’s direct neighbor.

The queuing mechanism for the integrated protocol is inspired by BEND protocol (Zhang et al., 2010) and consists of three different queues. A queue for control packets, Ctrl Queue, a queue for non-coded data packets, Non-Coded Queue, and a queue for packets which are to be sent as coded packets Q-mixing Queue. Their priority order is as follows: Ctrl_Queue, Q-mixing Queue and Non-Coded Queue. For a data packet, MAC layer checks whether this packet is to be sent in cooperative mode or non-cooperative mode (packets which are deemed beneficial in the cooperative mode, is marked and this is marked into the packet from the network layer). If a packet is to be sent in a cooperative mode, then it is placed at the tail of the Non-Coded Queue. If a packet is to be sent in a non-cooperative mode then the algorithm searches for other packets which are meant to be sent in a non cooperative mode in the data packet queues (Q-mixing and Non-Coded Queue) for which the coding condition is satisfies. If found the packet is placed at the tail of the Q-mixing queue along with the packet that can be coded with this packet. If the packet cannot be partnered with another packet to be coded together, then it is placed at the tail of the Non-Coded Queue. As opposed to (Zhang et al., 2010), integrated protocol stack does not have overheard packet queue because coding overheard packets is not allowed in the integrated protocol stack.

3.5.4 Decoding, ACK and Retransmission Policy

When a node receives a coded packet, it checks if it is on the list of receiving nodes. If so, the node decodes the packet with the corresponding stored packet that was sent before or overheard. For the purpose of decoding, node stores the packet it has forwarded, originated and overheard. After decoding the node sends ACK to the coded packet sender. Since the network coded packets are sent in broadcast mode, the 802.11 specification is not reliable here (in order to ensure the delivery of the data packet ACK packet is used, now when we network code multiple packets, there is no mechanism in 802.11 specification where the multiple recipients can send ACK, that is why we have adopted the sequential ACK/NACK sending back to the sending node as per (Zhang, et.al., 2010)). In order to ensure the reliability of data delivery, ACK/NACK procedure from protocol presented in (Zhang et al., 2010) is adopted. In this case the ACK/NACK header is modified shown in Figure 3.3, to include the source address instead of the recipients address and the unique packet-ID for which the ACK/NACK is meant for. When the coded packet sender node receives an ACK from a receiver, it deletes that packet from its repository as this packet has been already delivered to its next hop node. In the event the sender receives a NACK, it checks again if it can be coded with another combination, in the event it does satisfy the coding condition it is paired with that packet to be sent as network coded packet. In the event the sender does not receive any ACK/NACK for the sent coded packet, it assumes that there was a collision and reschedules this coded packet with doubled contention window (CW).

As for the non-coded packet in cooperative mode, after receiving a packet the node checks whether it is the recipient or relay node for this packet. If it is the relay node, it turns on the timer for hearing ACK for this packet from the receiver node. Overhearing this ACK, the relay node discards the packet. In the event packet was unsuccessfully received at the receiver, after the expiry of the timer for hearing ACK, the relay node forwards the stored packet copy to the receiver. After the arrival of the second packet copy, the receiver employs equal gain combining of the two packets (for details see e.g. (Lin et al., 2009)) and checks if the packet can be decoded correctly. At the same time, the source node, overhearing the transmission of the same packet from the relay node, deletes the packet as it has already reached the relay node (progress towards the destination). If the packet is received correctly at the receiver node, it sends ACK back to the relay node and the relay node deletes that packet from its repository. If the combined packet is still not received correctly, the receiver discards the packet. Then, since the relay node does not receive ACK for the packet, it sends the packet to the network layer to resolve the route to the destination. Then it is treated as a new packet that can be sent as native or coop or coded packet depending on the conditions and topology. The decoding and ACK/NACK packet sending procedure is depicted at Figure 3.6.

3.5.5 Prioritization of Coded Packet

In order to maximize the gain resulting from NC protocol, sending the coded packets should have priority within a node and between nodes. This two-level prioritization was proposed in (Zhang et al., 2010). Following this approach in our system the Q-mixing queue has priority over the Non_Coded_Queue to provide priority within a node. To provide priority for coded packets between the nodes, once the coded packet is selected for transmission in a node, the MAC algorithm checks if the medium is free and if so it applies a shorter contention window (CW) than the conventional one that increases the chance of seizing the channel (in case the CW window for coded packets and native packets are of equal length each node will contend for channel equally which removes the prioritization of the nodes for coded packet and this in turn will reduce the number of coded packets). Figure 3.7 shows the flow chart how the coded packets are prioritized among the nodes by selecting a shorter CW as compared to native transmission.

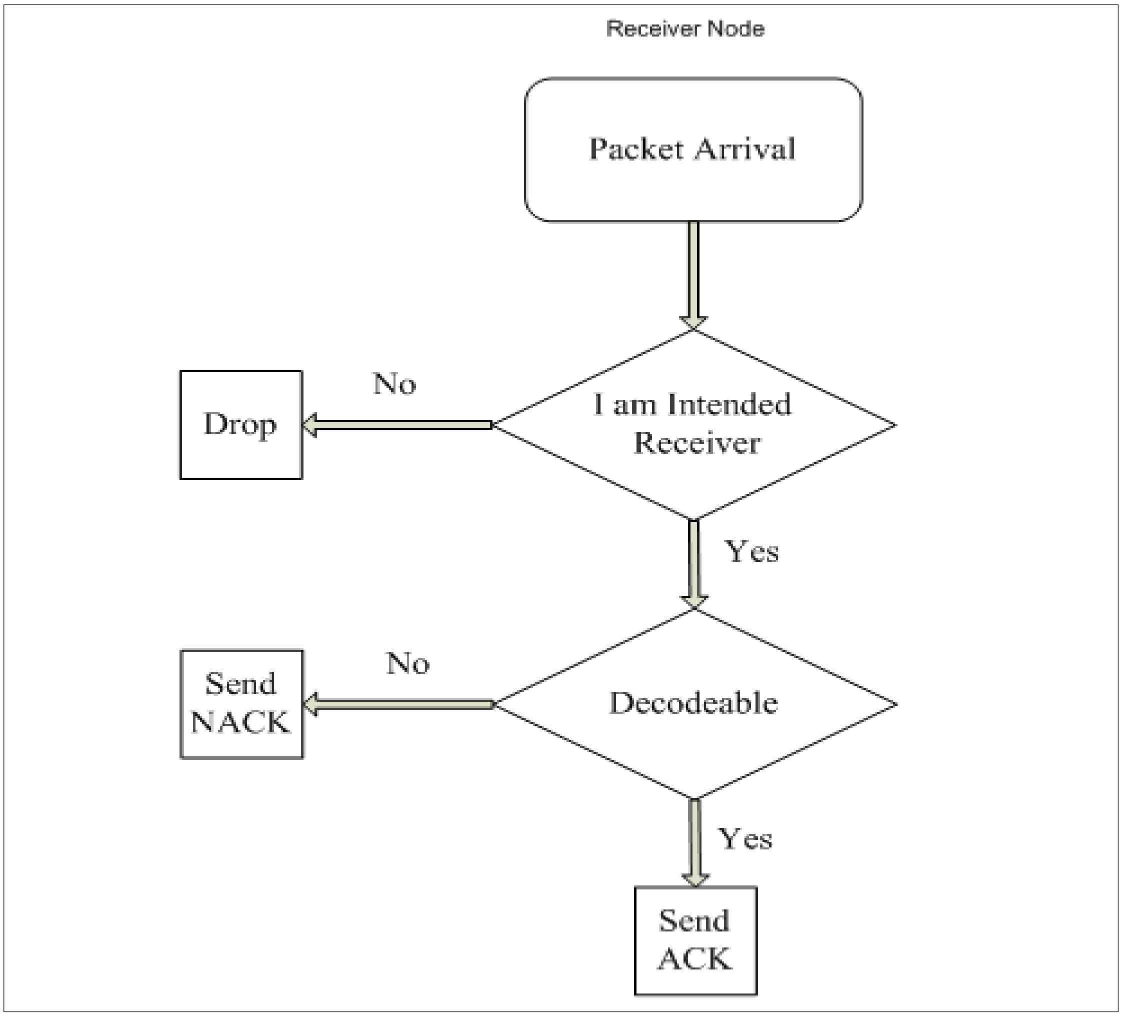


Figure3.6 Flow chart for decoding and ACK/NACK procedure

3.6 Physical Layer Modifications

For the cooperative diversity, equal gain combining has been employed at the physical layer. After receiving a packet, a node checks if this packet is sent in coop mode or non-coop mode. If the packet is sent in coop mode, and if the frame is not decoded correctly, it stores that packet, and waits for the relay nodes copy. When the relay node notices that the receiver did not send the ACK back to the source, if it has received the packet successfully, it relays the data packet on the next time slot. Once the receiver node receives the copy of the same packet from the relay node, it combines both the packet using equal gain combining (EGC) and then decodes it. For details please refer to (Lin et al., 2009).

3.7 The Integrated Architecture

The integrated protocol modules implemented in the protocol stack for WMN are illustrated in Figure 3.8. At the network layer, there is the neighbours database that stores information regarding the neighboring nodes. It stores the averages of the received SNRs, the MAC addresses and the modified queue lengths that are received via the HELLO packets at the network layer. Another module is the relay node selection mechanism. This module uses the neighbours database, and selects the relay node based on the potential gain from spatial diversity as well as the coding opportunity as described in Subsection 2.4.2. The last element in the network layer is the interface for cross-layer communication with the MAC layer. At the MAC layer, there is the priority scheduler that provides priority for the coded packets over the non-coded packets as described in Subsection 3.5.5. There is also the network coding/decoding module and the overheard packet repository that stores native packets overheard from the channel which are not addressed to the node. The interface for cross-layer communication with the network layer also resides in the MAC layer. At the physical layer, there is the packet buffer, which holds a packet received in error during cooperative transmission mode, and the equal gain combiner that combines two packets arriving via two independent paths.

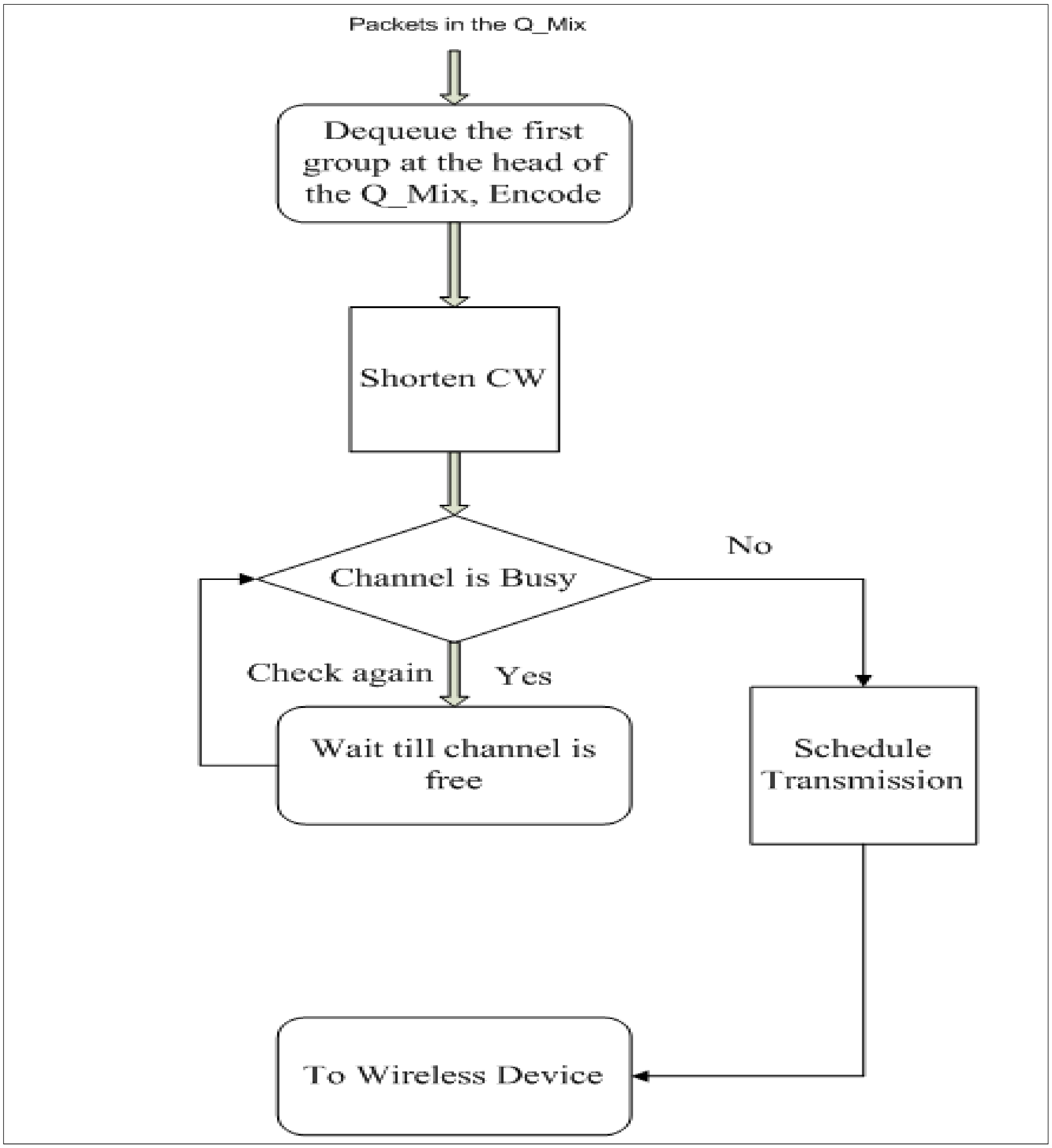


Figure3.7 Flow chart for sending coded transmission

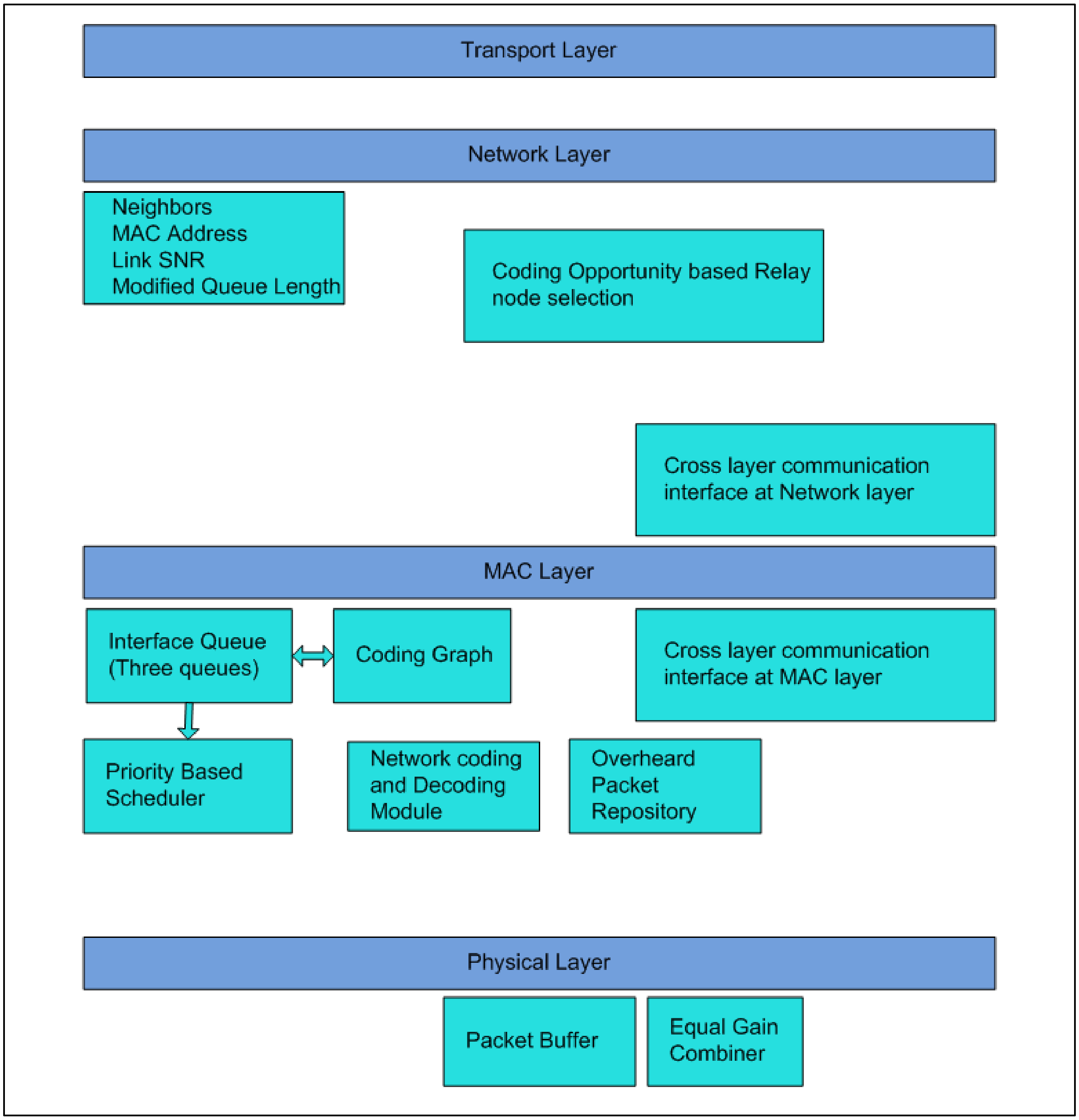


Figure 3.8 Integrated protocol modules in the protocol stack

Chapter Summary

In this chapter the objectives and the challenges for integrating the aforementioned mechanisms has been presented. In order to overcome the challenges for integration and capitalize on the broadcast nature of the wireless channel OSI reference architecture has been modified where the modifications has been carried out at the network, MAC and Physical layers. The module which required for each layer of the protocol stack has been discussed starting from network layer, MAC and Physical layer. Cooperation between network and MAC layer has been introduced, where these two layers frequently exchanges data which is a violation of the reference OSI architecture. This violation of the OSI reference architecture is being used as cross-layer based integration (INT-C).

CHAPTER 4

PERFORMANCE EVALUATION OF THE INTEGRATED PROTOCOL

Introduction

In this chapter the performance of the integrated protocol (INT) and integrated protocol where cooperation enabled between MAC and network layer (INT-C) is compared with the performance of the NC_BEND (network coding protocol BEND), CP (cooperative protocol), CP_RL (cooperative protocol where relay link is created at MAC layer) and the traditional 802.11(TH) protocol using extensive simulations. The performance of these protocols is evaluated using NS-3 based wireless network simulator. A probabilistic model is employed to account for successful and failed receptions. In this model the probability of successful reception depends on the modulation (the data rate at which the packet is transmitted) and the signal to noise and interference ratio for the packet received ((Lacage et al., 2006), (NS-3 Model-Library, 2012)). For INT, CP, CP_RL, NC_BEND, and TH protocols, receiver based auto rate selection algorithm (RBAR) (Holland et al., 2001) is adapted. IEEE802.11a has been used as the underlying MAC-layer mechanism. The data flows in the network are all CBR flows with data packet length of 1500 bytes and 0.001sec interval between successive packet arrivals.

The network employs AODV protocol for route discovery between the source and the destination. One point worth noting here is that the integrated protocol has been tested under saturated traffic, i.e., the source nodes always had data packets to send to the destination node. A simple question might be raised here is what happens if the integrated protocol is tested under light to moderate traffic condition? In order to have more coding opportunities, the developed protocol has been tested under saturated traffic, if the protocol is tested under light to moderate traffic, the gain from the network coding would be slightly diminish, but the gain from other mechanisms would be retained as the objective of the integrated protocol was to minimize the losses by leveraging the broadcast characteristics. The gain from CP as well as CP_RL would be retained and the objective of the integration would be fulfilled.

There are several factors which affect the performance of the integrated protocol. First is the spatial diversity. When we send packet from sender to a distant receiver, packets can be received in error or successfully. In traditional packet forwarding or network coding protocol whenever an error occurs, the node makes the assumption that the receiver is busy, so it doubles the contention window (CW) and schedules the packet after that if it wins the channel. Now for the cooperative protocol when a relay node agrees to cooperate, if a packet is not successfully received by the receiver, it abstains from sending ACK back to the sending node, on noticing this, the relay node forwards the data packet if it has overheard during the sending node's transmission (the likeliness of overhearing the sender's transmission at the relay node is much higher as the distance between the sender and the relay is smaller than the sender and receiver). This improves the reliability of the data packet at the same time, the sending node does not need to wait additional time after doubling its CW. This is one of the factor which influences the throughput. The second factor is opportunistic forwarding.

There we have two elements of opportunism in the integration. First is the control packet based. When a node sends RTS to the receiver, it includes the receiver and the relay nodes address. If the link is established between the sender and the receiver, the sender schedules the packet, and sends it to the receiver. Now if the reception at the receiver side is not successful, relay node forwards the packet. When the source overhears the transmission from the relay node for the same packet, it assumes that the packet is successfully received by the relay node and the forwarding responsibility is transferred to the relay-node. Now if the receiver node receives it successfully, then it sends ACK to the relay node instead of the sending node in the modified protocol. If the relay's transmission is not successfully received at the receiver, then it abstains from sending any ACK. After noticing this, relay node resolves the route to the next-hop, updates the route and then reschedules the packet as native or coded packet(if there is any coding opportunity arises). So we capitalize on the progress already made to the relay node towards the destination. Now the second form of opportunism comes from the control packet basis. When a node sends RTS to the intended receiver, if the reception is successful, it replies with CTS and a link is established. If the RTS-CTS packets are not successfully exchanged, in traditional protocol a node doubles its CW and waits for that amount of duration even if the relay node has successfully received the RTS and CTS packet, so link could have been established between the sender and the relay-node. We capitalize on that, if the link is not established between the sender and the receiver, the relay node after a SIFS + Ack_Timeout period, sends CTS back to the sender, upon hearing CTS from the relay node a link is established between sender and relay-node. This link-splitting mechanism is independent of the Network layer, as MAC is in charge of splitting the link. A part of gain comes from this link-splitting as we reduce the back off time which were wasted with traditional protocols. And the third part of the gain comes from the network coding protocol. Whenever coding opportunity arises, the relay node codes packet and saves the number of transmission. Thereby further improving the network throughput.

Now there is one more source from where the throughput improvement comes from and that is tie-in the route selection based on the capacity of the link and choosing the links only which met certain requirement. The data structure created at the network layer with the information coming from MAC layer is crucial for the performance improvement. It can be seen as a black box, which has two parts, one at the network layer and the one at the MAC layer. Now with the new form of cooperation enabled between MAC and network layer; MAC and network layer communicates more frequently than the traditional protocol. When a node receives a packet, it passes the SNR value and the MAC address of the transmitting node. At the network layer, the node stores averaged SNR values along with the MAC address of the transmitting nodes. These frequent communications/talking between the layers make it easier to predict the channel conditions, making it more robust to the channel variations and thereby improving the network throughput.

The performance of the protocols is tested for the following topologies: diamond topology, 3X3 mesh, 4x4 mesh and 16-node random topology. These topologies are illustrated in Figures 4.1-4.4. In section 4.1 we discuss the topology on which the performance evaluation was carried out, in section 4.2 we discuss the performance evaluation in terms of the network throughput, in 4.3 in terms of delivery ratio, 4.4 number of transmission required per packet delivery, 4.5 discusses the distribution of the different mechanism usage in the integrated protocol stack, 4.6 presents the gain from cooperation of network and MAC layer and in 4.7 a table is presented which shows how the gains from different mechanism sums up for integrated protocol.

4.1 Considered Topologies

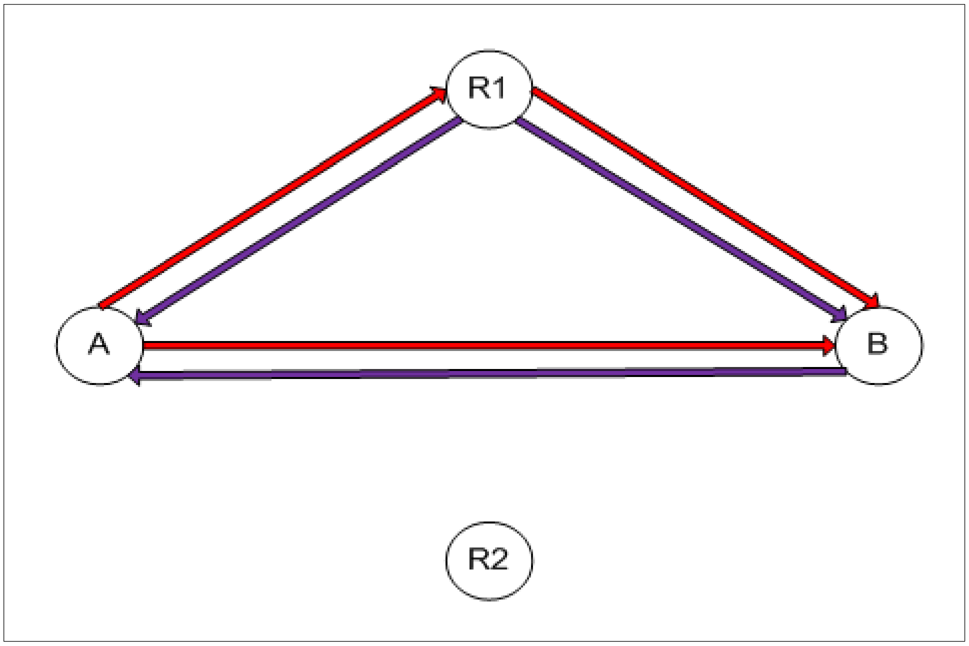


Figure4.1 Diamond topology

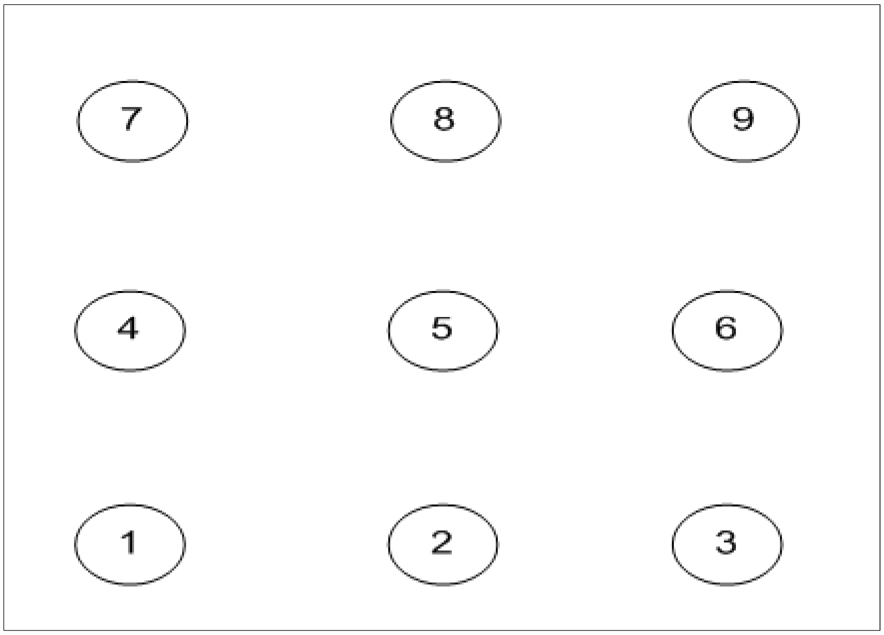


Figure4.2 3X3 mesh topology

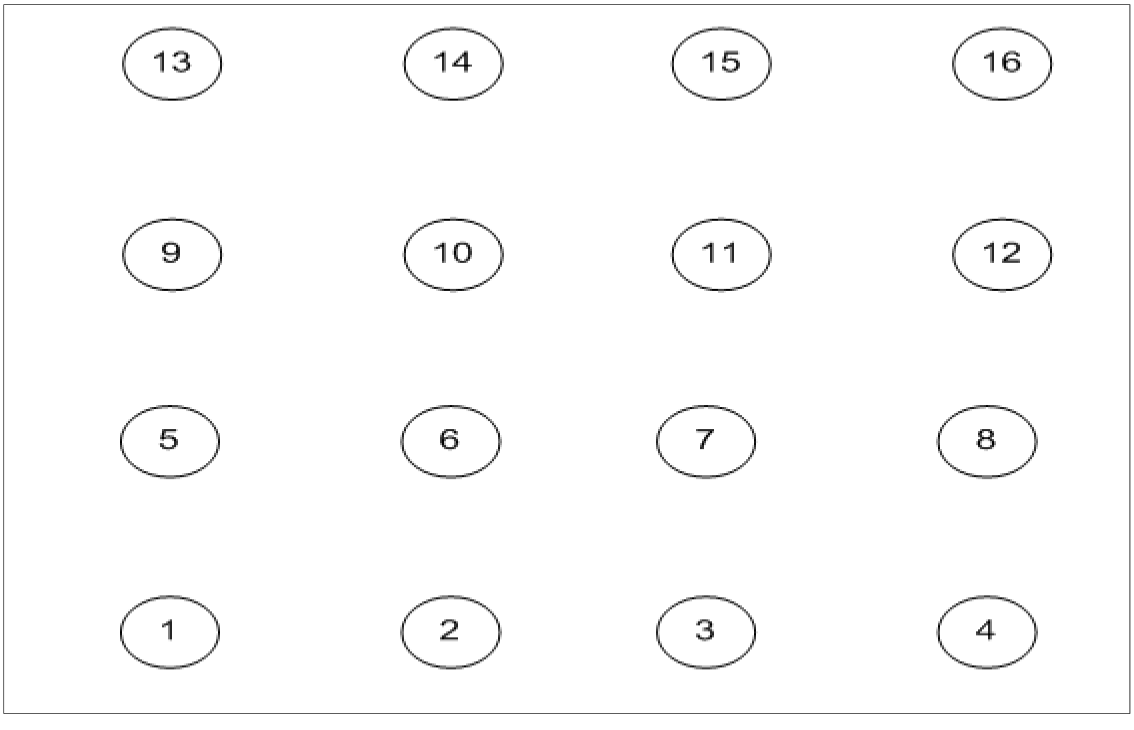


Figure4.3 4X4 mesh topology

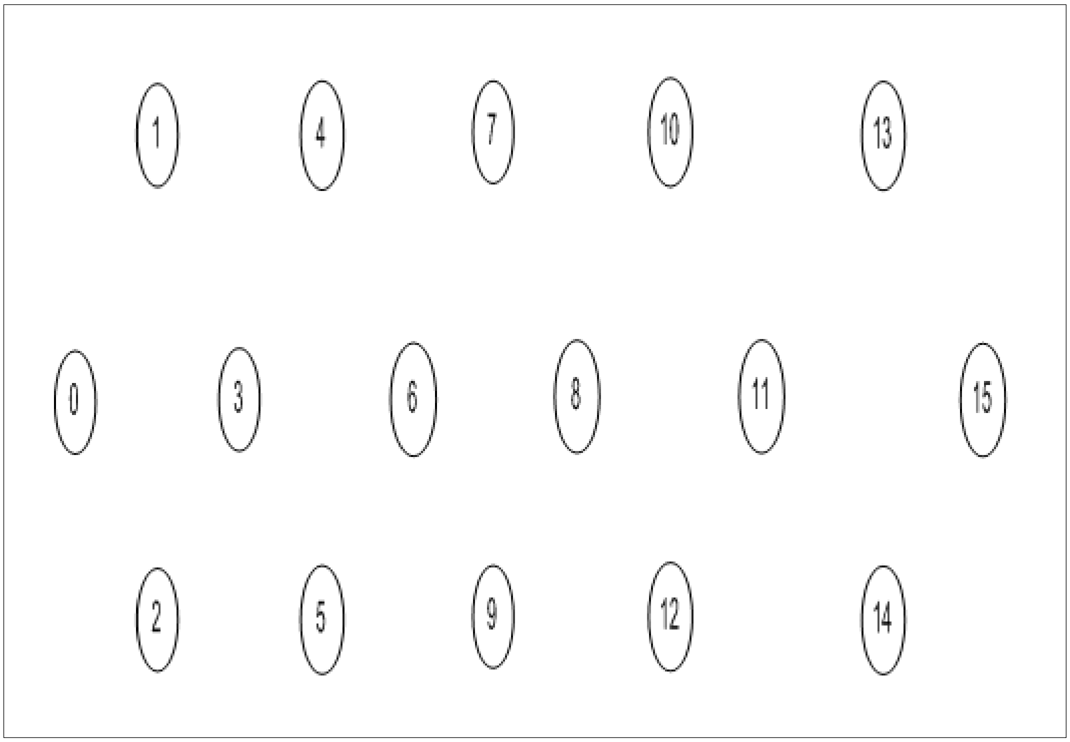
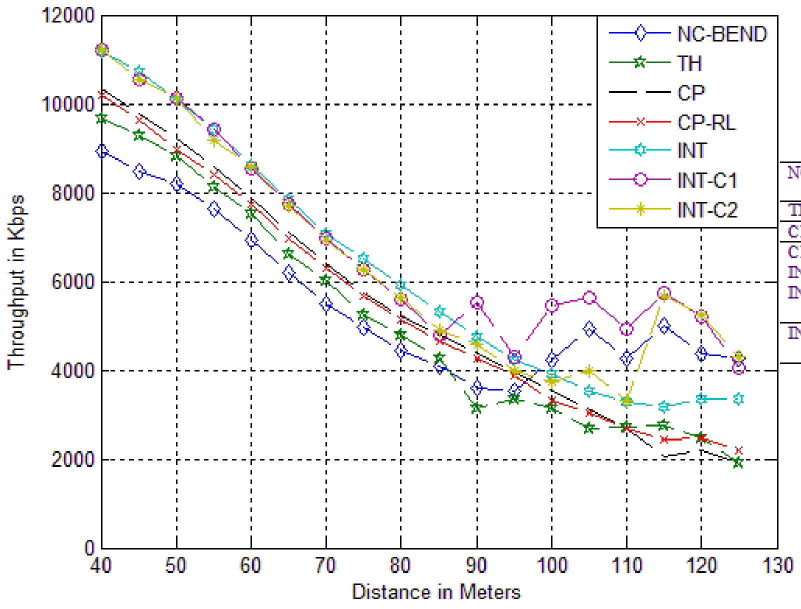


Figure4.4 16-node random topology

The protocols' performance is tested for the following topologies: diamond topology, 3X3 mesh, 4x4 mesh and 16-node random topology. These topologies are illustrated in Figures 4.1-4.4. In the diamond topology, illustrated in Figure 4.1, there are 4 nodes. Node A and B are in the direct communication range of each other and there are two nodes (R1, R2), located in equal distance from A and B, that can help in the data forwarding process. The distance between nodes A and B is varied from 40 to 125 meters. For each performance evaluation point, the simulation was carried for 110sec. No data is sent for the first 10sec in order to estimate the node-link metrics (in particular the received SNR based on the network layer control packets). Then the data traffic is injected from node A to B and then, after subsequent 2sec, the traffic from node B to A is added. In the 3X3 and 4X4 mesh topologies (Figures 4.2, 4.3) the vertical and horizontal distances between the nodes are 45m. The distances between the neighboring nodes (including the diagonal neighbours) are such that they can communicate with high success rates in order to leverage the coding opportunities.

In these topologies the traffic is generated between Node 1 and the opposite corner node (Node 9 in the 3X3 topology and Node 16 in the 4X4 topology). First, Node 1 starts to send data to the opposite corner node and then after 2sec the opposite corner node sends traffic to Node 1. The main objective for testing these two topologies is to verify how the nodes cooperate to forward the data packets and how the coding opportunities are discovered along the way. In the 16-node random topology (Figure 4.4) the nodes were placed in such a way that the flows must travel 4 or 5 hops before reaching its final destination. Two flows are generated. The first from Node 0 to Node 15 and the second, after 2sec, from Node 15 to Node 0. The aggregate end-to-end throughput (network throughput), the ratio of data packets received correctly at the final destination over the number of data packet transmitted by the source (delivery ratio), and the number of transmissions per packet delivery has been measured and used for comparisons. These performance characteristics are analysed in the following subsections.



NC_BEND	BEND networkcoding
TH	Traditional protocol
CP	Cooperative Protocol
CP_RL	Link creation at MAC based CP
INT	Integration of NC, CP and OR
INT-C1	MAC and network layer cooperation enabled INT, threshold 11db
INT-C2	MAC and network layer cooperation enabled INT, threshold 4db

Figure4.5 Network throughput for Diamond Topology vs. node A-B distance

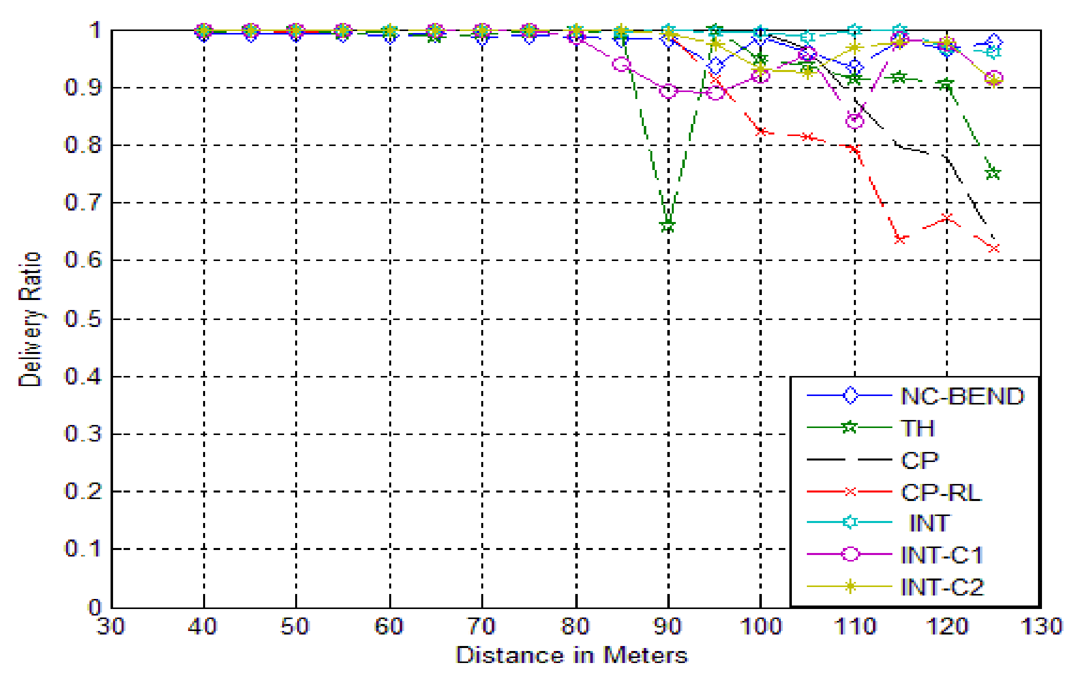


Figure4.6 Delivery Ratio for Diamond Topology vs. node A-B distance

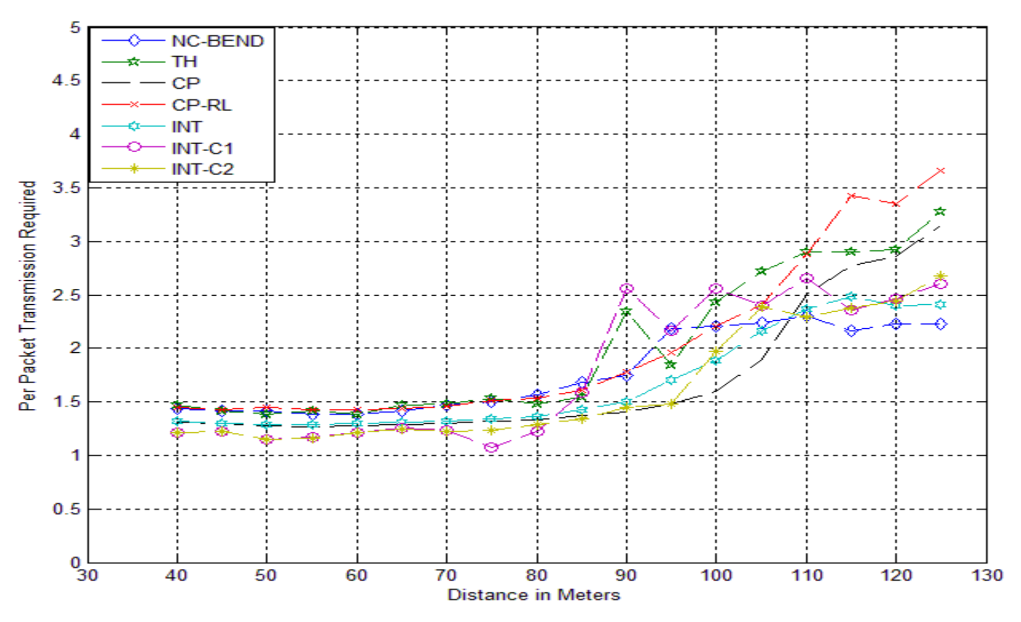


Figure4.7 Number of transmissions per packet delivery (NTPD) vs. node A-B distance

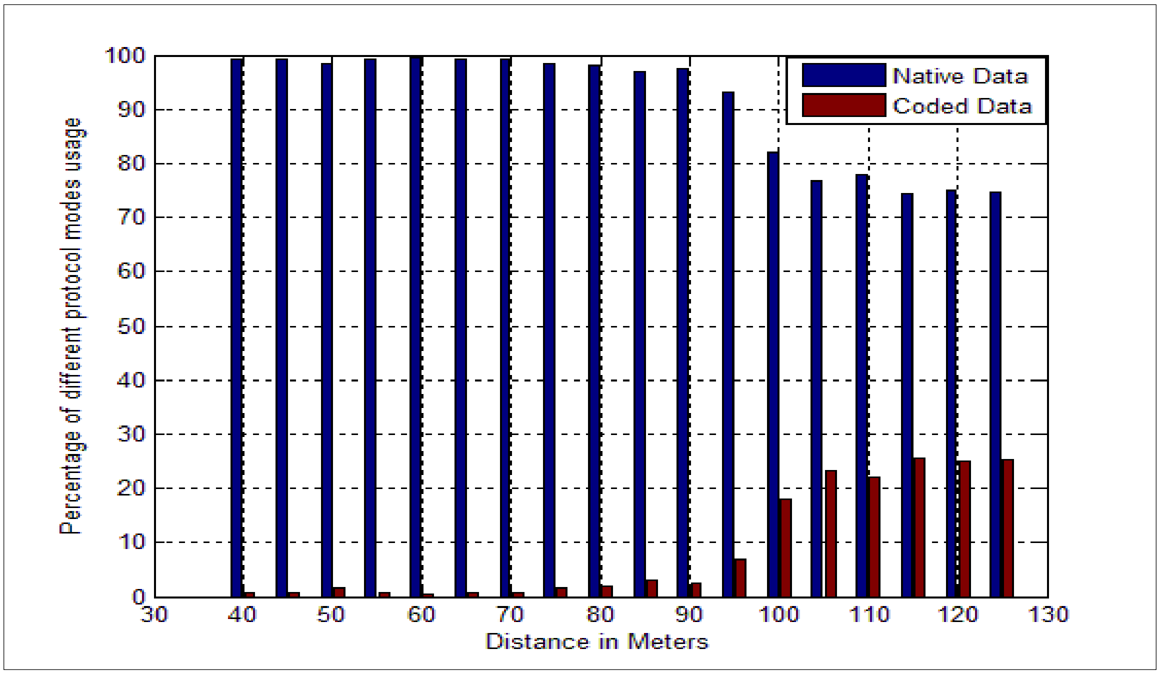


Figure4.8 Fraction of the packets sent in native and coded mode for the NC_BEND case vs. node A-B distance

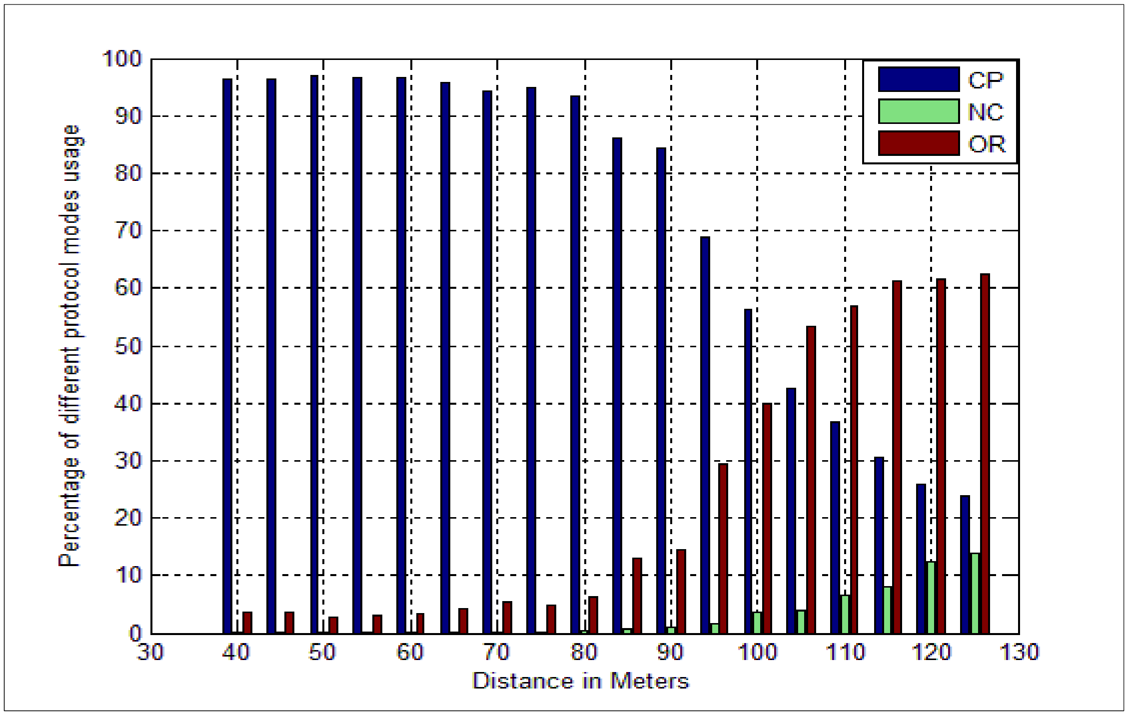


Figure4.9 Fraction of the three different mechanisms usage for the INT case vs. node A-B distance

4.2 Network Throughput

The network throughput is defined as the average rate (bytes per second) of all packets received correctly at the final destination nodes. We start from analysing the network throughput results for the diamond topology. Figure 4.5 shows the network throughput as a function of the A-B distance for NC_BEND, TH, CP, CP_RL, INT, INT-C1 and INT-C2 protocols. The two versions of the INT-C protocol have different SNR threshold values for the neighbor node selection: 11db for INT-C1 and 4db for INT-C2. The first interesting observation is that while the throughput of the INT protocol is higher than any of the individual protocols till 95m, it is lower than in the NC_BEND protocol for larger distances. The reason for this is that above 95m the A-B link is split into two links in the NC_BEND case while in the INT case the A-B link is not split but is in its grey zone (Hollande et al., 2001) and at this distance even the CP protocol fails to maintain a reliable direct link. Consequently the NC_BEND protocol takes advantage of two shorter links since the coding opportunity arises at the relay-node. This feature is illustrated in Figures 4.8 and 4.9 where the distribution of the CP, NC and OR mechanism usage is shown for the NC_BEND and INT protocols. The second interesting observation is that the throughput of the INT-C protocol is significantly improved above 95m distances when compared with INT and it is also higher than NC_BEND. This is due to two INT-C features. First, the neighbours (to which a node can send packets) are selected based on the link quality (average link SNR). Second, the data rate at which the packets are sent follows the average link SNR as opposed to the instantaneous SNR in RBAR (Holland et al., 2001).

As mentioned before we consider two SNR thresholds for INT-C. When the SNR threshold is set to 11db (INT-C1), there is a significant improvement in terms of the network throughput but the delivery ratio and the number of transmissions per packet delivery (NTPD) are worse than for the SNR threshold set to 4db (INT-C2), although in the INT-C2 case the network throughput is slightly reduced compared to INT-C1. These features can be observed in Figures 4.5, 4.6 and 4.7 showing the performance metrics vs. the A-B distance and in Tables 4.1, 4.2 and 4.3 where the average (over the distance) performance metrics are given. As can be seen from Figure 4.5, the throughput values for the TH, CP and CP_RL protocols are much lower, compared to the INT, INT-C1 and INT-C2 protocols, especially when the A-B distance increases. This is due to the fact that the direct communication in these protocols is being carried out at lower data rates while in the INT, INT-C1, INT-C2 and NC_BEND cases the data packets are sent at higher data rates and using the NC mechanism. The comparison of the network throughput for all considered topologies is given in Table 4.4. To simplify the presentation, only INT-C2, among the integrated protocol options, is considered for all multi-hop topologies. The results show that the throughput gains of the INT-C2 protocol are much more pronounced for multi-hop topologies. The biggest one (383% - 446%) are achieved against the traditional hop based protocol, TH, because in this case the nodes send packets without judiciously considering the link quality. When compared with the CP and CP_RL protocols, the gain of the INT-C2 protocol is in the range of (94% - 307%) and (50% - 180%), respectively. Note that the throughput of the CP_RL protocol is higher than the one for the CP protocol and this is due to the relay link creation at the MAC layer and employing opportunistic forwarding. Also, when compared with the NC_BEND protocol the throughput gains of the INT-C2 protocol are significantly higher (50%-78%) than in the diamond topology case. Moreover, it is interesting that the performance of the NC_BEND protocol for the 16-node topology is worse than the one for the CP_RL protocol. This is due to the fact that the CP_RL performs the link creation at the MAC layer while the NC_BEND protocol does not have coordination between network and MAC layer. It should be mentioned that the improved performance of the INT-C2 protocol in multi-hop scenarios is also due to the application the CDARM metric that is used to select minimum cost paths.

4.3 Delivery Ratio Analysis

The delivery ratio is counted as the ratio of the number of packets received correctly by the destination nodes to the number of packets sent from the origin nodes. In Figure 4.6 the delivery ratio is plotted vs. the A-B distance for the diamond topology case while in Table 4.2 the average (over the distance) delivery ratio difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP protocols, respectively, is presented. It can be seen that INT and INT_C2 improve the delivery ratio as compared to any other single protocol. On the other hand, the delivery ratio of the INT-C1 protocol is slightly lower when compared with the

NC_BEND case. This comes from the fact that when the SNR threshold is set to 11db, the nodes tend to send data packet at higher rates where the error probability is higher. In Table 4.5, the delivery ratio of the protocols is presented for all considered topologies. As in the case of the throughput metric, the gains of the INT-C2 protocol are significantly more pronounced when compared with the diamond topology case. The reason for this is that the INT-C2 protocol utilizes the NC mechanism as well as spatial diversity. While NC_BEND outperforms CP, CP_RL and TH protocols in terms of the delivery ratio for the 3X3 mesh topology, its delivery ratio degrades progressively for the 4X4 mesh and 16-node random topologies to the point that it is worse than the CP and CP_RL protocols for the 16-node random topology. Once again this is due to the lack of coordination between the network and MAC layers in the NC_BEND protocol. Moreover, the NC_BEND protocol was designed for single rate transmissions.

4.4 Number of transmissions per-packet Delivery

The number of transmission per-packet delivery, NTPD, is defined as the ratio of the number of packet transmissions made by the source and the intermediate nodes to the number of packets successfully received by the final destination nodes. NTPD for the diamond topology is plotted in Figure 4.7 vs. the A-B distance and the averages, over the distance, are given in Table 4.3. The results show that NTDP for the INT, INT_C2 protocols is smaller when compared with the TH, CP_RL, NC_BEND and INT_C1 protocols. CP protocol makes less transmission as compared to INT_C1, this is because in INT_C1 the neighbor selection threshold was too high and at 90m, the link is no longer direct, it being spitted in two hops. Table 4.6 presents NTDP for all considered topologies. For the 3X3 mesh topology, INT-C2 gives NTDP = 1.93, which is the lowest value among all the protocols. This is caused by the fact that in this case the data packets travel via two hops and employs coding of the data packets at the intermediate nodes or the relay nodes (2, 4, 5 or 6, 8). In the NC_BEND case we have NTDP = 2.74, which implies that the packets travel via more than two hops and this is due to the lack of coordination between the network and MAC layers. As the number of hops increases for the 4X4 mesh and 16-node random topologies, the gap between NTDP for INT-C2 and NC_BEND increases. Concerning the CP_RL protocols, only for the 16-node random topology the NTDP value for the INT-C2 protocol is slightly higher compared with the CP_RL protocol. This is due to the fact that the CP_RL protocol creates longer links and applies opportunistic forwarding, while in INT-C2 the links are selected based on the average received SNR threshold, so the packets travel through more hops compared to the CP_RL. Note that while the packets travel via more nodes in the INT-C2 protocol, the INT-C2 throughput is still higher than in the CP_RL. This is because in the INT-C2 case the data rate is related to the link quality and the path is selected based on the CDARM metric.

Table 4.1 Average network throughput difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP, CP_RL respectively, for diamond topology

Throughput Difference (%)	**TH**	**NC_BEND**	**CP**	**CP_RL**
INT	21	13	14	15
INT-C1	32	23	24	25
INT-C2	25	16	17	18

Table 4.2 Average delivery ratio difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP, CP_RL respectively, for diamond topology

Delivery Ratio (%)	**TH**	**NC_BEND**	**CP**	**CP_RL**
INT	6.5	1.5	6.4	12.9
INT-C1	2.8	-1.85	2.9	9.1
INT-C2	5.1	0.19	4.9	11.2

Table 4.3 Average NTPD difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP, CP_RL, respectively, for diamond topology

NTPD (%)	**TH**	**NC_BEND**	**CP**	**CP_RL**
INT	-14	-6.3	1.0	-14
INT-C1	-11	-2.0	6.8	-10.3
INT-C2	-18	-9.7	-3.2	-18

Table 4.4 Network throughput for different topologies

Topology	**Protocol**	**Network Throughput(Kbps) X1e+003**
Diamond	TH	5.14
	CP	5.49
	CP_RL	5.44
	NC_BEND	5.53
	INT	6.24
	INT-C1	6.79
	INT-C2	6.43
3X3 Mesh	TH	1.14
	CP	1.36
	CP_RL	1.98
	NC_BEND	3.68
	INT-C2	5.54
4X4 Mesh	TH	0.29
	CP	0.49
	CP_RL	0.89
	NC_BEND	1.16
	INT-C2	1.80
16 Node Random	TH	0.39
	CP	0.69
	CP_RL	0.90
	NC_BEND	0.75
	INT-C2	1.34

Table 4.5 Delivery ratio for different topologies

Topology	**Protocol**	**Delivery Ratio**
Diamond	TH	0.94
	CP	0.95
	CP_RL	0.90
	NC_BEND	0.97
	INT	0.99
	INT-C1	0.96
	INT-C2	0.98
3X3 Mesh	TH	0.34
	CP	0.50
	CP_RL	0.63
	NC_BEND	0.89
	INT-C2	0.97
4X4 Mesh	TH	0.11
	CP	0.20
	CP_RL	0.41
	NC_BEND	0.33
	INT-C2	0.51
16 Node Random	TH	0.10
	CP	0.23
	CP_RL	0.31
	NC_BEND	0.19
	INT-C2	0.44

Table 4.6 Number of transmissions per packet delivery (NTPD) for different topologies

Topology	Protocol	Transmission Require Per Packet Delivery
Diamond	TH	1.99
	CP	1.7
	CP_RL	2.0
	NC_BEND	1.77
	INT	1.68
	INT-C1	1.78
	INT-C2	1.62
3X3 Mesh	TH	7.03
	CP	3.94
	CP_RL	4.06
	NC_BEND	2.74
	INT-C2	1.93
4X4 Mesh	TH	22.44
	CP	11.6
	CP_RL	7.86
	NC_BEND	8.40
	INT-C2	6.0
16 Node Random	TH	14.84
	CP	8.8
	CP_RL	7.98
	NC_BEND	10.99
	INT-C2	8.15

Table 4.7 Fraction of time usage of different mechanism

Topology	CP	NC	OR
Diamond	75	8	17
3X3	54	22	24
4X4	58	8	34
16 node	64	8	28

In table 4.8, the comparison MAC and network layer cooperation enabled integration of NC, CP and OR mechanism is presented in terms of network throughput, delivery ratio and number of transmission per-packet delivery in percentage improvement. In can be clearly seen that the integrated protocol performs best under mesh-topology in terms of all the three metrics. Employing the integrated protocol for Mesh network improves the performance of the network in terms of network throughput, delivery ratio and well as the number of transmission per packet delivery which in turn translates to less energy consumption per packet delivery and to improvements in the energy efficiency and therefore makes the network greener when compared to any protocol employed in isolation. Our finding for the best performance improvement is in accordance with the findings of (M. Elhawary, et.al,. 2011) where the authors presented their findings about the performance of CP protocol alone and concluded that the performance of their protocol yields the best performance gain when the nodes are arranged in the grids (mesh topology).

Table 4.8 Performance comparison of integrated protocol with protocols developed in isolation

Improvement in Network Throughput	**3 X3 Mesh**	**4 X4 Mesh**	**16 Node**
TH	446%	538%	241%
CP	311%	271%	92%
CP_RL	181%	104%	43%
NC_BEND	52%	63%	80%
Improvement in Delivery Ratio			
TH	189%	352%	334 %
CP	94%	156%	85%
CP_RL	55%	24%	39%
NC_BEND	8%	53%	134%
Reduction in Number of Required Transmission			
TH	-72%	-73%	-45%
CP	-51%	-48%	-7%
CP_RL	-53%	-24%	2%
NC_BEND	-30%	-28%	-26%

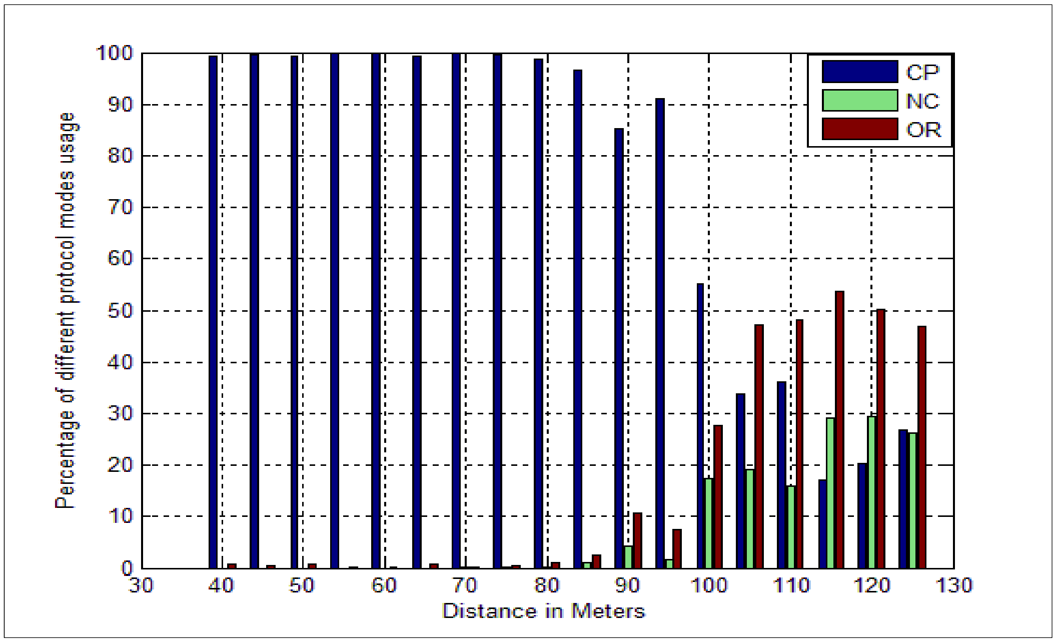


Figure 4.10 Fraction of the three different mechanisms usage for the INT-C2 case vs. node A-B distance

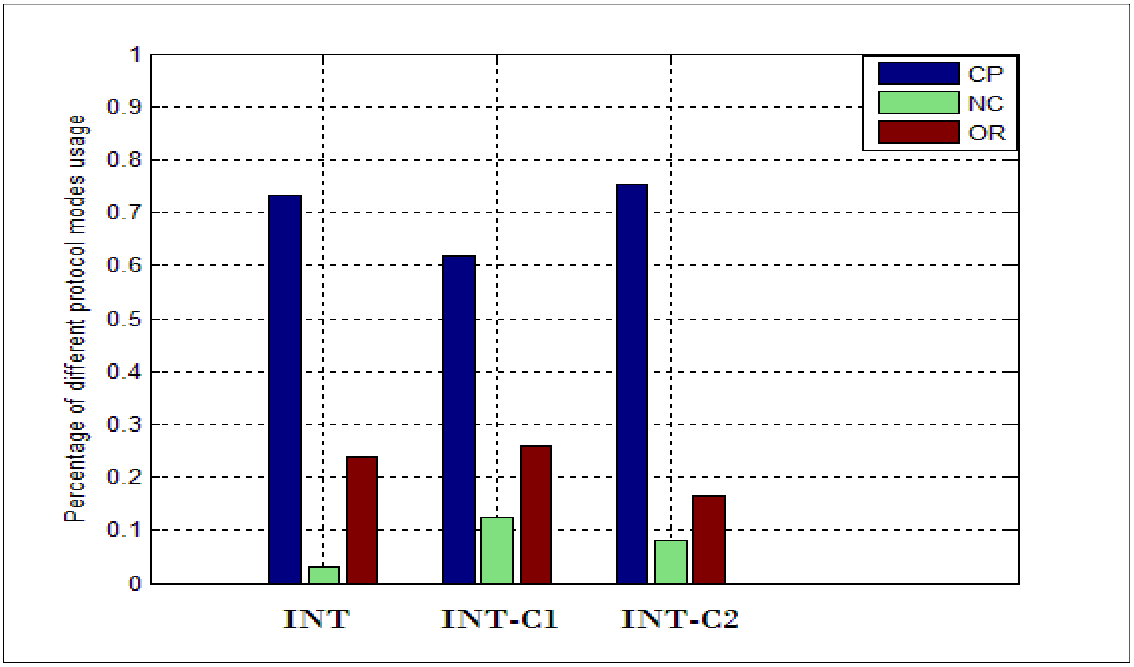


Figure 4.11 Average fraction of the three different mechanisms usage in the integrated protocols for Diamond Topology

4.5 Distribution of CP, NC, OR mechanisms usage in INT and INT-C2

In this section we analyse distribution of the CP, NC and OR mechanisms usage in the INT and INT-C2 cases. Figures 4.9 and 4.10 show the distribution of the CP, NC, and OR mechanisms usage in the INT and INT_C2 protocols for the diamond topology as a function of the A-B distance. The figures indicate that, as the A-B distance grows, the NC and OR mechanisms become more active in the INT_C2 protocol when compared to the INT protocol. Figure 4.11 shows average fraction of the CP, NC and OR usage in the integrated protocols. The CP, NC, and OR mechanisms usage distributions in INT-C2 for all considered topologies are presented in Table 4.7. For the diamond topology, the share of the CP mechanism is highest, although the shares of NC and OR mechanisms increase gradually as the A-B distance increases. It is interesting to note that in the 3X3 mesh topology the NC and OR mechanisms are almost equally active but the OR mechanism becomes more active as the number of hops travelled by packets grows.

4.6 Gain from Cooperation between Layers

In order to test how the cooperation between the network and MAC layers affects the performance of the network, we compare the performance of this mechanism, implemented on a traditional packet forwarding mechanism, with the case where there is no cooperation between the layers. Figure 4.12 shows the performance comparison in terms of the network throughput for the diamond topology. It can be seen that the cooperation between the MAC and network layers alone provides significant improvement in terms of network throughput with average of 18%. Note that implementation of this cooperation does not require any meta data to be conveyed; the throughput improvement is achieved just by averaging the SNR received from a distant node, judiciously choosing the neighboring nodes and the data rate at which the data packet is sent is based on the average SNR to that neighbor. Although this form of cooperation reduces the delivery ratio by 3.4% but on the other hand it reduces the required number of per packet transmission by 10.24%.

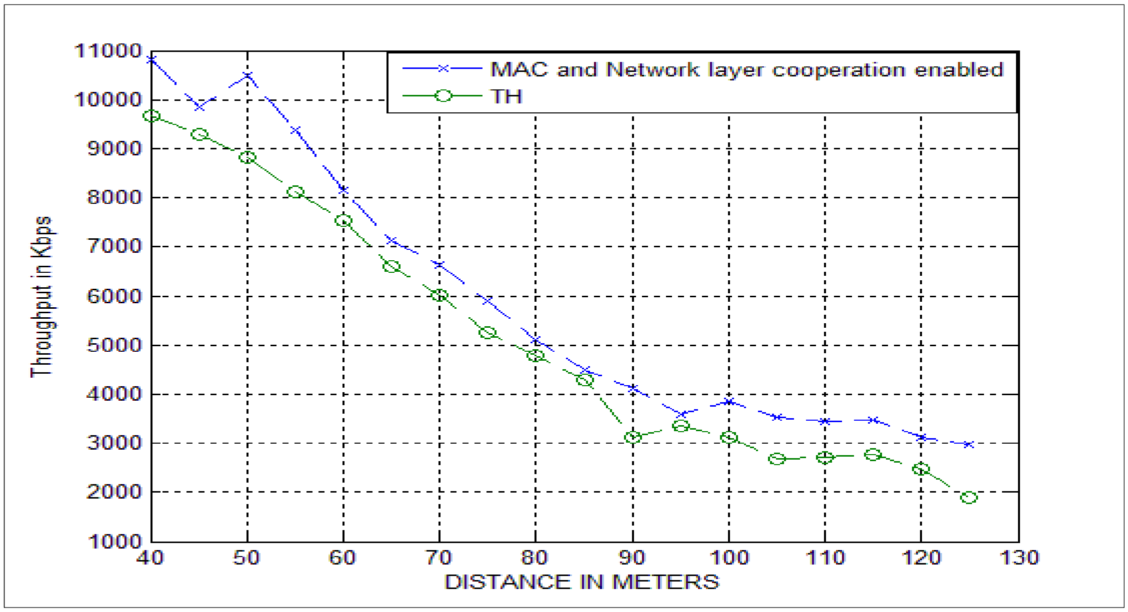


Figure 4.12 Network throughput for Diamond Topology vs. node A-B distance

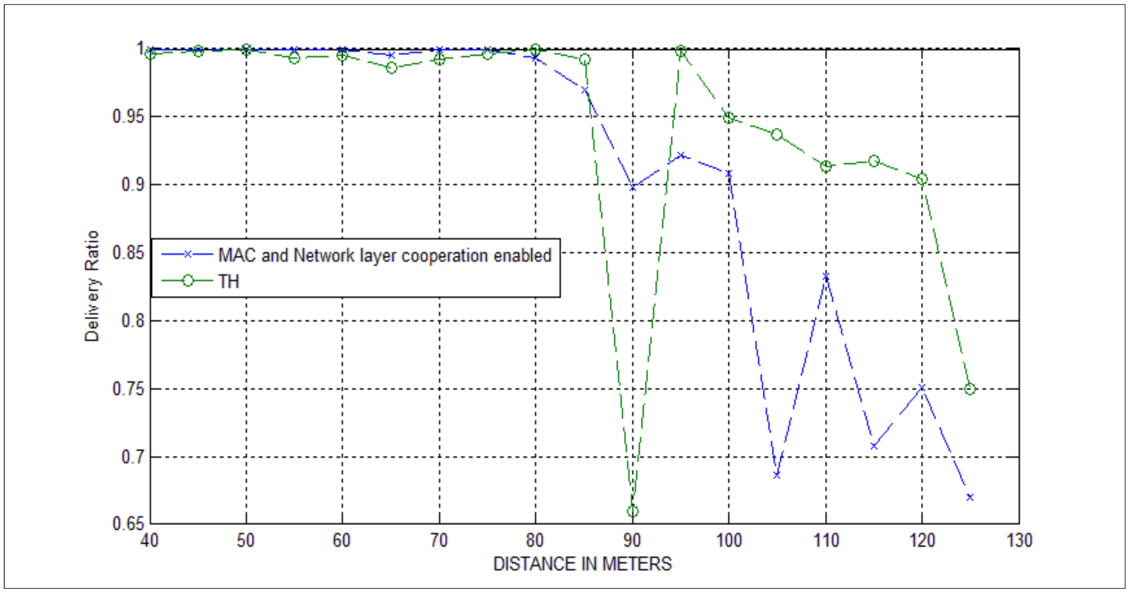


Figure 4.13 Delivery Ratios for Diamond Topology vs. node A-B distance

4.7 Analysis of Gains from Integration of NC, CP and OR Mechanisms

The gain from different protocol can be combined to give us a formula where we can calculate the gain for integrated protocol and for the each mechanism. For example, if the gain over traditional protocol from NC:-X, OR:-Y and CP:-Z, then we wanted to establish how the combined gain is related to individual gain.

$$G = K(X+Y+Z)$$

Table 4.9 Gain table for the combined gain formula

Gain Over TH (%)				
Topology				
Topology	**Diamond**	**3X3 mesh**	**4X4 mesh**	**16 node random**
NC_BEND	23.0	221.0	299.0	90.0
CP	6.0	73.0	68.0	129.0
CP_RL	7.0	19.0	205.0	75.0
INT_C2	25.0	384.0	538.0	241.0
Gain Factor K	0.69	1.22	0.94	0.82

On the last row, the gain factor have been arranged, from there we can easily see that the gain factor for integrated protocol is maximum in 3X3 and 4X4 mesh topology. It can be clearly seen from the Table 4.9 that the gain is maximum for the mesh topology as in this case there is ample opportunity for cooperation as well as network coding at the intermediate and relay nodes. It is also interesting to note that the gain factor is maximum for 3X3 mesh network; this gives us an indication about placement of the access points connected to the wired internet (IGW). For 4X4 mesh, if we placed IGW nodes at 1, 4, 13 and 16, the users will experience much better performance in terms of network throughput, delivery ratio and number of transmission per packet delivery as can be seen from the table where the gain for the network and MAC layer cooperation enabled integration is more than the sum of the gains from three mechanisms when considered in isolation. How the users connect with the nearest IGW can be an interesting avenue for future investigation (this topic is beyond the scope of this work).

Chapter Summary

Integration of the NC, CP and OR mechanism results in the network performance improvements. Our study shows the performance improvements in terms of the network throughput, delivery ratio and number of transmission required per packet delivery. Integration of these three mechanisms also has some implied benefits. As mentioned, the number of transmission required per packet delivery is reduced significantly as compared to any single protocol in isolation. These reductions of the number of required transmissions results in reduction of energy required per packet transmission, which in turn improves the battery life of the nodes or devices. From the simulation results presented in this chapter, it can be concluded that the integrated protocol works best for the Mesh topology cases. This follows from the fact that in the mesh topology the nodes are placed at a regular interval and there are diagonal nodes which facilitate cooperation, link creation at the MAC layer and network coding along the way to the final destination.

CONCLUSION

Wireless mesh networks offer solution to the last mile problem but currently the offered throughput is inadequate for next generation applications. To improve the performance we considered integration of three mechanisms: network coding, spatial diversity and opportunistic routing/forwarding that capitalize on the broadcast nature of wireless links to improve the network performance. These techniques target different network conditions and usually are considered in separation. In this thesis a cross-layer based integration of the mentioned three techniques is presented to accumulate their potential gains using the same network protocol stack in wireless mesh networks. The proposed integration approach is based on a new CDARM metric used for the route selection and a method for creating relay links at the MAC layer. The numerical study based on system level simulations shows significant improvement in terms of network throughput and reliability. To the best of our knowledge this dissertation is the first attempt to integrate network coding, spatial diversity, and opportunistic routing/forwarding mechanisms in the same protocol stack. The modifications required to implement the integrated protocol can be easily incorporated in future generation devices.

Contributions

Integrated protocol stack provides a novel method to harness the gains from different protocols.

- Link creation at the MAC layer, combines opportunistic forwarding and cooperative protocol. The simulation results show that integrating the opportunistic forwarding with cooperative protocol improves the network performance;
- Integration of network coding, spatial diversity and opportunistic routing/forwarding shows the improvement of network performance;
- Introduction of MAC and network layer cooperation (cross layer) to the integrated protocol. The work presented in this thesis, shows a novel method for cooperation between the MAC and network layer and its effects on the network performance.

Future works

There are several issues that could be investigated to further improve the performance of the integrated protocol, the main being:

- Intra-session network coding can be added on to the protocol stack along with the integration;
- Integrated protocol can be applied to LTE/WIMAX network to improve its performance;
- Reactive cooperation can be implemented and tested in the integrated protocol stack;
- A new routing metric can be designed for Cooperation between MAC and network layer;
- The future network architectures are moving towards software defined networking, an interesting avenue of research would be to incorporate the protocols that are presented in this dissertation into software defined networking architecture.

APPENDIX I

INTEGRATION OF NETWORK CODING, SPATIAL DIVERSITY AND OPPORTUNISTIC ROUTING/ FORWARDING IN WIRELESS MESH NETWORKS

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Abstract

Network coding, spatial diversity and opportunistic routing/forwarding leverage the broadcast nature of the wireless links to improve the network performance. These techniques target different network conditions and usually are considered in separation. In this article a cross-layer based integration of the mentioned three techniques is proposed to accumulate their potential gains using the same network protocol stack in wireless mesh networks. The proposed integration approach is based on a new CDARM metric (Coding opportunity and Data rate Aware Routing Metric) used for the route selection and a method for creating relay links at the MAC layer. Based on the system level simulation our results demonstrate that the integration can improve significantly the performance in terms of network throughput and reliability.

Index Terms— Network coding; Spatial diversity, Opportunistic routing, Link creation at MAC layer.

I. Introduction

The Wireless Mesh Network (WMN) technology can provide low cost broadband internet to the users but multihop routing, broadcast nature of transmission medium and channel dynamics cause degradation of the network performance. While the traditional mechanisms, coping with these issues, mask the broadcast ability that is inherent to the wireless channels, more recent research starts to leverage this broadcast ability instead of treating it as an adversary. In particular there are three promising mechanisms belonging to this category: Network Coding (NC), Spatial Diversity (SD) and Opportunistic Routing (OR). Network Coding (NC) works in the Shim layer between Network and MAC layers (Katti et al., 2008). By mixing multiple packets together through some algebraic operation, it requires less number of transmissions which improves the performance. Spatial Diversity (SD) has been proposed to overcome the detrimental effects of fading and interference (Foschini et al., 1998), (Telatar et al., 1999). To realize the gain from SD, cooperative protocols (CP) have been proposed (Laneman et al., 2004), (Sendonaris et al., 2003) as a feasible alternative to MIMO techniques that are not always feasible due to space constraints of the device (Sadek et al., 2010). In CP, nodes in the vicinity of the transmitter and receiver (referred to as relays) help in the transmission by forming a virtual antenna array. In the remainder of this paper the term CP is used in the sense of SD. Opportunistic Routing (OR) selects a subset of neighboring nodes which are closer to the destination than itself to capitalize on the broadcast nature of the links (Biswas et al., 2005), (Yuan et al., 2005). More recent work, (Rozner et al., 2009), suggests selecting the next hop forwarder not just based on proximity to the destination but also the inter-node distance among the next hop nodes, to suppress divergent paths and duplicate transmissions. While the objective of the NC, CP and OR mechanisms are the same (reducing the number of transmission), they are usually considered in separation and the related protocols are quite different.

A question may be posed, whether it is possible to integrate these three mechanisms in a common network protocol stack to accumulate the gains they offer. The main challenge is to bring these gains into a single platform, so that the gain from one mechanism does not sabotage the gains from other mechanisms, i.e., to create cohesion in the functioning of these three mechanisms. In order to realize this, several issues need to be addressed and resolved, the main being: selection of relay nodes for cooperation, coding opportunity detection along the route, expediting coding packets transmissions and improving the spectral efficiency.

In order to address the above issues, a cross layer approach to perform integration of the three broadcast based techniques is proposed in this paper. This approach is based on a new metric, Coding and Data rate Aware Routing Metric (CDARM), used for the route selection. The CDARM metric defines where cooperation and network coding are possible and beneficial. Also, relay links creation mechanism is introduced at the MAC layer. This mechanism uses a relay node when the direct link is weak and employs opportunistic forwarding. To the best of our knowledge no prior attempts have been made to integrate these three mechanisms on to the same protocol stack. The main objective for NC, CP and OR mechanisms integration is to accumulate gains from the three different broadcast based mechanisms in WMN. Also, we want to assess how far is the integrated gain from the sum of the individual gains, since each mechanism can work optimally under different network characteristics. One of the distinct features of the integrated protocol stack is that the CDARM metric combines the link capacity, topology, traffic load and interference information together in a unified manner. Another distinct feature is the cooperation between the network and MAC layers. The proposed integration approach shows significant improvement in performance as compared to any single mechanism protocol. Our contributions can be listed as follows:

- A new routing metric is proposed (CDARM) that detects coding and cooperation opportunities;
- A MAC layer relay link creation method is devised which splits a link into two shorter links at the MAC layer on the fly, in an on demand fashion;
- A new form of cooperation between MAC and network layer is introduced. This cooperation facilitates the route selection as well as data rate for sending data packets at the MAC layer;
- Detailed modified network protocol stack for integration of the three broadcast based techniques is developed.

The rest of the article is organized as follows. The review of existing works is given in Section II. Section III presents the performance metrics and the integration approach. The design details, system architecture and implementation details are described in Section IV. The simulation results are presented and analyzed in Section V that is followed by conclusions.

II. Previous works

The MORE protocol (Chachulski et al., 2007) proposes integration of the OR and NC protocols. The results show that MORE improves performance of the network when compared with the EXOR protocol (Biswas et al., 2005) and it also removes the need for global coordination among the next hop forwarders, however it requires complex hardware (Kim et al., 2013). In (Yan et al., 2010) the CORE protocol selects a group of forwarders which are close to the destination and the forwarding priority among these forwarder nodes is selected based on coding opportunities. The CORE protocol maximizes the number of packets send in each transmission but it is designed for fixed bit rate network. In (Manssour et al., 2009) the performance of network coding was evaluated in presence of an opportunistic relay node selection. Based on the results, the authors conjecture that the selection of the relay node should take into consideration the coding opportunity which may arise in the relay node but no practical means is proposed for coding opportunity detection. The BEND protocol (Zhang et al., 2010) implements network coding and opportunistic forwarding in the network protocol stack. In this protocol there is no mechanism introduced to combat the fading which is inherent to the wireless channel. The BEND protocol was designed for fixed data rate transmission; whereas data rate selection mechanism is important for performance of the network (Kumar et al., 2010). Also the BEND protocol makes minimal assumption about the routing protocols. In the remainder of this paper we refer to this protocol as NC_BEND protocol. The NCAC-MAC protocol (Wang et al., 2014) proposes another integration of the CP and NC protocols. It does answer an important question of how to cooperate when the direct transmission from the transmitter to the relay node fails. It supports two forms of cooperation: network coded cooperative retransmission and pure cooperative retransmission. The authors compare its performance with CSMA and Phoenix (Munari et al., 2009) protocols. The NCAC-MAC protocol was designed for single hop networks, which is not suitable for WMN. In (Kafaie et al., 2015), authors provide a mechanism for forwarding coded packets even when the recipients are not the intended receiver. The authors have considered a two-ray model and only the base data rate was considered in the data forwarding mechanism while performance analysis for multi-rate networks is not provided. In the INCUR protocol (Zhu et al., 2015), integration of NC and

OR has been presented. The authors propose a new metric for the integration NC and OR protocols. This protocol was designed for basic data rate. The analysis presented in this paper employs probabilistic estimation of coding chances in the metric. However, when applied to multi-rate case this analysis becomes invalid since a link that is strong at the base rate can be weak or very weak at the higher data rates. In (Antonopoulos et al., 2013) the authors have performed integration of cooperative protocol with network coding from energy efficiency perspective. Their results also indicate that integrating NC with cooperative protocol results in improved performance in terms of throughput as well as delay. This protocol was designed for single hop scenario, where the transmitter and receiver are within the communication range of each other and in between them there are some helper nodes. This protocol is not suitable for wireless mesh network where we need to have multi-hop forwarding. In (Koutsonikolas et al., 2008), the XCOR protocol is proposed for single rate network. It integrates NC with OR and is based on the ETX metric that does not takes into account the multi-rate capability of the network.

III. Proposed integrated protocol

The proposed integrated protocol stack is based on the IEEE 802.11 based MAC protocol where DCF mechanism is employed for the contention. In the following we describe the elements of the integration and the integrated protocols functioning.

Basic Building Blocks

In the following, the considered implementation of each mechanism is presented first and then the integrated protocol stack is described. For illustrations, a simple four node network topology is used, as shown in Figures A I-1 and A I-4, where nodes A and B exchange packets and nodes R1, R2 are the relay nodes used to improve performance.

NC Protocol

The NC mechanism is illustrated in Figure A I-1. In this case nodes A and B have packets for each other, but since they are out of direct communication range they use an intermediate node R1 for packet forwarding. When traditional packet forwarding is applied, the exchange of two packets from, one from A to B and one from B to A, requires 4 time slots (2 slots per packet). When network coding is applied the two packets are coded into one at R1 and the coded packet is broadcast to A and B at the same time allowing to decode the destination packets at A and B. Therefore only 3 time slots (1.5 slots per packet) are used. The saved one time slot is the coding gain.

CP Protocol

In this case Nodes A and B are in direct communication range. Node A has packet P1 for B and it selects also node R1 as the relay node according to the relay node selection criteria (Lin et al., 2009). Then the packet is forwarded with the data rate appropriate to the current channel state between A->B. If the direct transmission is successful, node B sends ACK back to node A. The relay node does not intervene in this case as illustrated in the timing diagram from Figure A I-2a. If the direct transmission is unsuccessful there is no ACK sent by B so the relay node forwards the packet after the SIFS period as illustrated in the timing diagram from Figure A I-2b. Combining two copies of the received packet at node B yields diversity gain that increases the likelihood of correct reception. There can be more relay nodes to aide in the communication but selecting only one relay is sufficient to achieve diversity order (Zhuang et al., 2013). Therefore in this paper we limit consideration to one relay node.

OR Protocol

In the OR protocol, a node selects a group of next hop forwarders that are closer to the destination than the node itself. The selection is based on a metric. Coordination among next hop forwarders to eliminate duplicate transmissions is an issue that can be dealt via some organized packet exchanges (Boukerche et al., 2014). Figure A I-3 illustrates a classification of OR protocols based on the type of coordination as described in (Boukerche et al., 2014). In RTS/CTS based coordination, before sending the data packet, a node sends RTS to the group of neighbouring nodes, where the node ID-s are ordered based on the priority according to a metric. If the highest priority node receives the sent RTS, it sends back CTS packet after SIFS period. After overhearing this RTS/CTS exchange, the remaining nodes in the group turn on their NAV (network allocation vector) and the forwarding link is established with the highest priority node. If the highest priority node does not send CTS, the second node in the group sends CTS after 2*SIFS period and so on. We have employed a similar approach between the sender, receiver and relay node, by creating relay links at the MAC layer as explained in the following paragraph.

Relay Links at MAC Layer (CP_RL protocol)

Suppose node A has a packet to send to node B and network layer selects to cooperate with node R1. Then node A sends RTS with highest priority for node B and second priority for node R1. If B receives RTS successfully it replies with CTS, after the successful exchange of these handshake control packets, node A sends packet to B. When the relay node receives RTS, it checks whether it is an intended receiver/relay node, and when it learns it is a relay, it turns on a timer. If it does not hear CTS back from the receiver B, it sends CTS to the sender node A after SIFS + CTS_timeout period. If the RTS packet is received successfully at node B but the CTS packet is received in error at node A, node R1 notices this because there is no transmission from A to B after certain duration. Then, if the CTS packet was received successfully at the relay node, it sends CTS packet back to node A and the communication is established between node A and node R, this creates the relay links A-R1 and R1-B at the MAC layer. After successfully receiving the packet at R1, it opportunistically forwards the packet to the next hop node B along the route. So the next hop as fixed by the network layer is changed at the MAC layer and the link is created to bypass the broken link. This is independent of the Network layer. This is the form of opportunism which was introduced onto the network protocol stack for the purpose of integration (In the traditional protocol when a node sends RTS to a receiver, if the handshake is not successful between the source and the receiver, then the source node assumes that there is a collision as there is no mechanism to separate between transmission failure due to erroneous reception or due to collision. The source node doubles the contention window and waits for that doubled CW + DIFS amount of time before sending RTS packet again to the receiver node. It does not take the advantage of whether there was any other node with which link can be established which is closer to the destination than itself. In the integrated protocol this is capitalized when the source node fails to establish a direct link in L_S-{R}-L_D, it establishes links as L_S-R and R-L_D in opportunistic fashion). We have employed the AODV routing protocol, that is why the relay node can forward packets to L_D, there are other options which can be implemented to change the route completely towards the destination from the relay node if a link-state routing protocol is employed, since in the link-state routing protocol every node is aware of the other nodes and has route to any destination available. Another option which can be implemented is that if we store the 2NH-(next-hop's next hop) as suggested in (Zhang et al., 2010), then the relay node may choose to select the 2NH node as next hop or any other node which has link-to the 2NH node along the route. To minimize the complexity we have chosen to employ opportunistic forwarding from the relay node to the next-hop. In the remainder of the paper CP_RL denotes the CP protocol based on relay link creation at the MAC layer.

Integrated Protocol Functioning

Let us explain the integrated protocol functioning using the same network topology example that was used for illustration of each mechanism separately. Suppose there is a direct link from A and B and a relay node R1 to assist in the communication. Also suppose that there is a link from B to A that also selects R1 to be the relay node. Node A has 5 packets (P1, P2, P3, P4, P5) addressed to B and node B has 5 packets (P6, P7, P8, P9, P10) addressed to A. P1 is sent from A to B and if direct transmission succeeds, the relay node does not intervene, see Figure A I-4a (i). For P2, see Figure A I-4a (ii), the direct transmission is not successful, so the packet is relayed by R1 in the second slot. After receiving the second copy of P2, the two copies of the received packet are combined at node B and decoded successfully. Then node B sends ACK to the relay node. Note that after the relay node transmission, node A knows that packet P2 was forwarded by the relay node. We refer to this packet transfer as the CP transfer. For P3, see Figure A I-4b(i), the direct transmission is not successful, so the packet is relayed through the relay node in the next slot. After receiving the second copy of P3 by node B, the two copies are combined but the decoding is unsuccessful so node B does not send ACK. Note that after the relay node transmission, node A knows that packet P3 was forwarded by the relay node, so it moves to the treatment of the next packet. Since the relay node did not receive any ACK from the receiver node B, it forwards P3 to the network layer to resolve route to final destination and determines the next hop node, which could be also node B. We refer to this transfer as the OR transfer since it opportunistically changes the previously established route.

In order to illustrate the network coding integration, we assume that node R1 selected node B as the next hop node for P3 and that in the next slot (6th) node B gains the channel and sends RTS to node A, but the RTS packet is not received by A. Then, after the timeout period, R1 sends CTS packet back to B and a link is established between B-R1 and node B transfers packet P6 to R1, see Figure A I-4b (ii). Note that this transfer also falls into the OR transfer category. Then node R1 notices that it can code together packet P3 with P6, and sends the coded packet to A and B in a single slot as shown in Figure A I-4c(i) and A I-4c(ii).

Node-Link Metric

Our integration approach is based on a node-link metric (CDARM). This metric is used to select a route towards the destination and the potential relay nodes. Apart the link data rate, it takes into account coding opportunities as well as opportunities for cooperation. The metric for link A-B is given as follows:

$$CDARM(A-B) = \frac{1 + Modified\ Interference\ Queue\ Length(A)}{Data\ Rate(A-B)} \tag{A I -1}$$

Below we define the elements of this metric.

Modified Queue length

First the modified queue length is measured within a node. For example say there are three flows F1, F2, and F3 passing through a node. If flow F1 and F2 can be coded together, their contribution in the queue is counted as max (*f1, f2*), where *f1* and *f2* are the numbers of packets from flow F1 and F2 respectively. Then the modified queue length is defined as follows:

$$MQ(A) = \max(f1, f2) + f3 \qquad \text{(A I -2)}$$

Modified Interference Queue Length

The modified queue length is not sufficient to measure the traffic load in the node since it does not take into account the packet load in the neighboring nodes. In order to take this issue into account the Modified Interference Queue Length metric has been proposed in (Le et al., 2008):

$$MIQ(A) = MQ(A) + \sum_{i=1}^{n} MQ(i) \qquad \text{(A I -3)}$$

where *i* is the index of the neighboring nodes. Finally the link data rate is estimated as

$$Data\ Rate(A - B) = BW * log2(1 + SNR(A - B)) \qquad \text{(A I-4)}$$

where BW is the A-B link bandwidth. The costs of using R1 and R2 as relay nodes is defined as

$$L1 = CDARM(A - R1) + CDARM(R1 - B) \qquad \text{(A I-5)}$$

$$L2 = CDARM(A - R2) + CDARM(R2 - B) \qquad \text{(A I-6)}$$

Then the path with minimum cost is chosen for the relay selection. For example if L1 is the minimum-cost path then the algorithm checks if using relay node R1 is beneficial according to the following criterion

$$CDARM(A - B) > 0.5(CDARM(A - R1) + CDARM(R1 - B)) \qquad \text{(A I-7)}$$

If this condition is satisfied, using R1 as the relay node is beneficial. Note that the numerator of (A I-1) is associated with the node and the denominator is associated with the link. In this way, the CDARM metric combines the node and the link metrics. The criteria for selection of the path and the path selection procedure are described in Section IV.

III. Design And Implementation Details

Objectives and challenges

It is well known fact that NC protocols are sensitive to erroneous channels and while CP as well as OR protocols result in performance improvements under lossy channel condition. The main challenge is to bring gains from these protocols into a single platform, so that gain from one protocol does not sabotage the gain from other protocols, i.e., to create cohesion in the protocols functioning. In order to design the integrated protocol the following issues are carefully address.

- Selection of relay nodes for cooperative diversity and improving spectral efficiency. This issues are described in the node-link metric section
- Employing opportunistic forwarding: Link creation at the MAC layer as well as capitalizing on the progress already made by the packet towards the destination.
- Expediting the coded packets transmission: In order to maximize the coding chances coded packets must be prioritized for transmission within a node and among the nodes.
- Duplicate packet suppression: When opportunistic forwarding and network coding are employed, the protocol must ensure that duplicate packets are not transmitted by other nodes along the routes.
- Enhanced NAV update procedure for coping with cooperative protocol as well as the link creation at MAC layer protocol.

In order to address these issues, the network architecture needs to be modified by introducing additional functionalities into the network protocol stack. In the following, the details of the modified architecture are presented starting with network layer, then MAC layer and finally the physical layer.

Network Layer

For the purpose of integration, AODV routing protocol (Perkins et al., 2003) have been chosen to discover route in an on-demand fashion. A link-state routing protocol may be used as another option. Concerning the link metrics used in AODV, in the literature they are broadly categorized as topology based and load based metrics. Example of topology based metrics are hop-based, ETX, ETT, etc. and for load based metrics one can mention traffic intensity and interference aware metrics (Karia et al., 2013), (Sheshadri et al., 2014). In our implementation, the applied AODV protocol is based on the node-link metric, CDARM, proposed in Section III Node-link metric, which is a combination of topology based and load based metrics. The advantage of using node-link metrics is that it guides the packets on the path where coding opportunity may arise and also it weighs whether using that path is beneficial or not since a path may be good for coding but using an alternative path can be more beneficial due to the characteristics of the links along the path.

Restraining the RREQ packets

In conventional AODV protocol, a node that receives a route request packet, RREQ, for the first time updates its route back to the source node without judiciously considering whether the link via which the packet came is strong or not. Also in the conventional ETX metric based routing, a node processes the RREQ packet from the origin or the neighboring nodes only if the ETX metric, of the link by which the RREQ packet came, is above or equal to the given threshold. These threshold values are estimated using the number of control packets which are sent at the basic data rate. In this case, when employing multi-rate transmission at the MAC layer for forwarding the data packet, the transmission becomes prone to errors because of the channel dynamics. In order to overcome this difficulty, in our implementation, moving average of the link SNR has been employed. Therefore the routing decisions are not solely based on the number of control packets a node receives during a period of time but also on the average link SNR. In this case the routing criteria can be described as follows:

- Select a set of paths that meet certain criteria (in particular the average link SNR is above a given threshold).
- Then select a path with minimum cost.

This strategy allows the nodes to choose only those routes that are strong. Moreover it reduces the flooding of the RREQ packets which can result in network congestion.

RREQ phase

When source node S wants to establish route to destination node D it broadcasts the RREQ packet with the destination address and routing information. When a node receives RREQ, it first checks if the link meets the minimum average SNR requirements. If the requirements are met, it checks if it has already processed a request with the same RREQ_ID. If yes, the packet is discarded, otherwise the node estimates the CDRAM metric from the previous hop node and then it checks if using a relay node is beneficial for communicating with the previous hop node in terms of the CDARM metric as stated in the node-link metrics description in Section III C. If using the relay node is beneficial then it stores the relay node's address when creating the route to the origin (which is reverse route). Then the node checks if it has route to the destination. If there is no route to the destination, it includes the path cost up to itself from the origin in to the RREQ header. Then the node updates info in the RREQ header and broadcast it. The gratuitous reply is allowed (i.e., any node who has route to the final destination is allowed to reply on behalf of the destination node). In this process the cost of the entire path L is calculated as

$$CDARM_L = \sum_{l \epsilon L} CDARM_l \quad \text{(A I-8)}$$

RREP phase

When an intermediate node notices that it has route to the destination or the RREQ arrives at the destination node, then it sends reply back to the node from which it received the RREQ.

When an intermediate node sends the reply back it checks whether this new flow can be coded with any other existing flow. If yes, then it recalculates the MIQ value and the node-link metric, and inserts it to the RREP header. Upon receiving RREP, any intermediate node learns about the coding opportunities at if there any (the node that receives RREP) and estimates the CDRAM metric that is added to the path cost. This process continues till the RREP finally arrives at the source node. At the source node, if this is the first RREP for that destination, the routing information for that destination is stored along with its cost and the next-hop information. The source node also checks if there is an opportunity to cooperate with nodes which can be beneficial, according to the relay node selection criteria described in section III Node-link metric, and then adds the relay nodes addresses to the routing table for that destination. If the source node receives another RREP for the same destination with smaller cost than the previous route, then it removes the previous route and stores the new one.

Opportunism in the routing protocol

Opportunism is introduced into the routing protocol when a cooperative link is split at the MAC layer (as explained in more details in Section III - OR protocol). Then a new link is established between the sender and the relay node and in this case the packet transfer control is transferred to the relay node. In this case the relay node can forward the packet to the original next hop, or to another node that has a path to the destination with a smaller cost.

Cooperation among the MAC and Network layer

Cooperation among the network and MAC layer is extremely important as they are dependent on each other. In the proposed approach a node learns about its neighbors and the link quality between those nodes and itself as well as the link quality among those nodes by snooping on the channel in promiscuous mode. This information is stored in a data structure at the network layer and the MAC layer successively keeps this data structure updated. Note that this cooperation does not incur any extra overhead in terms of communicating meta data to the neighbors, as it is done by snooping on the channel in promiscuous mode as well as the exchange of the "HELLO" packet which is used for conveying the meta data to estimate the routing metric. This data structure is used by the network layers to select the strong neighbors as well as for the routing decisions. Also, after the establishment of the route, the MAC layer consults this data structure for selection of the data rate. Therefore, there is a two way communication between the MAC and network layer. This cooperation between network and MAC layer has been applied to the integrated protocol option that is referred to as INT-C (where C comes from the Cross layer enabled integration).

Header modifications

In order to differentiate between the coded, non-coop-native and coop-native packets, the MAC header is enhanced. When a packet is sent in the non-coop-native mode, its header is similar to the 802.11 specification except for the fact that the frame control sub-field is marked as non-coop-native. When a packet is sent in the coop-native mode, its RTS, CTS, DATA and ACK headers are enhanced as presented in Figure A I-5. The third address, RLY, represents the relay node with which the transmitting node wishes to cooperate. When coded packets are sent, the frame control sub-type is marked as coded. There is an array of addresses which are the recipient of the coded packets. Namely, the second address is the sender's address, and we have an array of packet-IDs that are intended for the nodes whose addresses are included in the array of recipients address, Code_Len represents number of packets being coded. The ACK packet contains the SA (data packets recipient address) instead of RA (data packet sender address) and the unique packet ID for which the ACK is destined.

Enhanced NAV for relay link creation

Consider the cooperative mode for link A-{R1}-B. First, node A sends the RTS packet with the addresses of receiver B and relay node R1. Suppose that the link is not established between A-B but instead the link is established between A-R1. In the 802.11 based Network Allocation Vector (NAV) mechanisms, the other nodes (the nodes which are in the vicinity of the transmitter and the receiver node) loose the chances for transmission even after the successful exchange of data packet. The reason is that when a node sends the RTS packet, it includes the duration for which the channel may be occupied with its last known channel condition. In cooperative mode this time can be described as CTS_Timeout + Data_Xmission_Time(A) + SIFS + Data_Xmission_Time(R1) + SIFS + ACK_Timeout. Same is true when we employ the cooperative protocol. Even if the direct transmission is successful, the nodes which are in the vicinity of the transmitter and the receiver node, still keep the NAV on because the NAV update does not employ a judicious update procedure for NAV. In the event the relay link is created at the MAC layer as described in section III, the data transmission time is halved, but the current NAV fails to take it into account. In order to cope with this, the NAV update mechanism has been modified. In the new NAV update procedure, when a node overhears a packet, it checks first for the sender and receiver addresses and the type of the packet. For example if the node receives RTS packet, it stores the sender and receiver addresses, and the duration which is indicated in the header. Then, if it overhears CTS within certain duration (CTS time out period) and if the CTS recipient is the same as last RTS sender, it stores the info also for the CTS sender. Then, if the next packet is data packet sent between the last heard RTS sender and receiver, then it updates the duration which is mentioned in the data packets header. If the data packet transfer is successful, the receiver node sends ACK back to the sender of the data packet and any node in the vicinity who has overheard the RTS/CTS exchange, updates its NAV instead of waiting for it to expire. This NAV update is especially important for multi-rate protocols. For example, suppose node A sends RTS to node B and according to the last known channel condition it estimates NAV based on packet length/(data rate (6mbps)). After successful exchange of RTS/CTS node A sends data packet at 18mbps according to the current channel condition so the duration of the channel occupation is packet length/(data rate 18mbps) which is much smaller than what was estimated before. If the judicious NAV update is not employed, the nodes in the vicinity of the RTS/CTS sender and receiver will be quiet for three times longer than required.

Queuing and Coding Policy

In the integrated protocol, packets can be coded only at the relay and intermediate nodes along the path. The coding structure is limited to two hops. Then, the necessary and sufficient conditions for coding two data packets, P1 and P2, together are:

- P1's next hop is P2's previous hop or P1's next hop is P2's previous hop direct neighbor;
- P2's next hop is P1's previous hop or P2's next hop is P1's previous hop direct neighbor.

The queuing mechanism for integrated protocol is inspired by BEND protocol (Zhang et al., 2010) and consists of three different queues. A queue for control packets, Ctrl Queue, a queue for non-coded data packets, Non-Coded Queue, and a queue for packets which are to be sent as coded packets Q-mixing Queue. Their priority order is as follows: Ctrl_Queue, Q-mixing Queue and Non-Coded_Queue. For a new data packet, the MAC layer checks whether this packet is to be sent in the cooperative mode or non-cooperative mode If a packet is to be sent in the cooperative mode, then it is placed at the tail of the Non_Coded_Queue. If a packet is to be sent in the non-cooperative mode then the algorithm searches for other packets which are meant to be sent in non cooperative mode in the data packet queues (Q-mixing and Non_Coded_Queue) for which the coding condition is satisfies. If found the packet is placed at the tail of the Q-mixing queue along with the packet that can be coded with this packet. If the packet cannot be partnered with another packet to be coded together, then it is placed at the tail of the Non_Coded Queue. As opposed to (Zhang et al., 2010), integrated protocol stack do not have overheard packet queue because coding overheard packets is not allowed in the integrated protocol stack.

Decoding, ACK and retransmission policy

When a node receives a coded packet, it checks if it is in the list of receiving nodes. If so, the node decodes the packet with the corresponding stored packet that was sent before or overheard. For the purpose of decoding a node stores the packet it has forwarded, originated and overheard. After decoding the node sends ACK to the coded packet sender. Since the network coded packets are sent in broadcast mode, the 802.11 specification is not reliable here. In order to ensure the reliability of data delivery, ACK/NACK procedure from protocol presented in (Zhang et al., 2010) is adopted. In this case the ACK/NACK header is modified, as shown in Figure A I-5, to include the source address instead of the recipients address and the unique packet-ID for which the ACK/NACK is meant for. When the coded packet sender node receives ACK from a receiver, it deletes that packet from its repository as this packet has been already delivered to its next hop node. In the event the sender receives NACK, the coding search procedure looks for a packet which can be coded with this packet. If such a packet can be found, the packets are placed at the head of the Q_Mix queue, otherwise the packet is scheduled to be sent as the native packet. In the event the sender does not receive any ACK/NACK for the sent coded packet, it assumes that there was a collision and reschedules this coded packet with the contention window (CW) doubled. As for non-coded packets in cooperative mode, after receiving a packet the node checks whether it is the recipient or relay node for this packet. If it's the relay node, it turns on the timer for hearing ACK for this packet from the receiver node. If overhearing this ACK, the relay node discards the packet. In the event packet was unsuccessfully received at the receiver, after expiry of the timer for hearing ACK, the relay node forwards the stored packet copy to the receiver. After the arrival of the second packet copy, the receiver employs equal gain combining of the two packets (for details see e.g. (Lin et al., 2009)) and checks if the packet can be decoded correctly. At the same time, the source node, after overhearing the transmission of the same packet from the relay node, deletes the packet as it has already reached the relay node (progress towards the destination). If the packet is received correctly at the receiver node, it sends ACK back to the relay node and the relay node deletes that packet from its repository. If the combined packet is still not received correctly, the receiver discards the packet. Then, since the relay node does not receive ACK for the packet, it sends the packet to the network layer to resolve the route to the destination. Then the packet is treated as a new packet that can be sent as native or coop or coded packet depending on the conditions and topology.

Prioritization of Coded Packets

In order to maximize the gain resulting from the NC protocol, coded packets should have priority within a node and between nodes. This two-level prioritization was proposed in (Zhang et al., 2010). Following this approach, in our system the Q-mixing queue has priority over the Non-Coded Queue to provide priority within a node. To provide priority for coded packets between the nodes, once the coded packet is selected for transmission in a node, the

MAC algorithm checks if the medium is free and if so it applies a shorter contention window (CW) than the conventional one in order to increase the chance of seizing the channel.

The Integrated Protocol Architecture

The integrated protocol architecture is presented in Figure A I-6.

IV. Simulation Results

In this section the performance of the proposed integrated protocols (INT, INT-C) is compared with the performance of the NC_BEND, CP, CP_RL and the traditional IEEE 802.11 (TH) protocols using extensive simulations. The performance of these protocols is evaluated using NS-3 based wireless network simulator. A probabilistic model is employed to account for successful and failed receptions. In this model the probability of successful reception depends on the modulation (the data rate at which the packets are transmitted) and the signal to noise and interference ratio for the packet received ((Lacage et al., 2006), (NS-3 Model-Library, 2012)). In the INT, CP, CP_RL, NC_BEND, and TH protocols, receiver based auto rate selection algorithm based on instantaneous SNR (RBAR) (Holland et al., 2001) is adapted while in the INT-C protocol the rate selection is based on the average link SNR. IEEE 802.11a is used as the underlying MAC-layer mechanism. The data flows are modelled as CBR flows with data packet length of 1500 bytes and 0.001sec interval between successive packet arrivals. The network employs the AODV protocol for route discovery between the source and the destination.

Considered Topologies

The protocols’ performance is tested for the following topologies: diamond topology, 3X3 mesh, 4x4 mesh and 16-node random topology. These topologies are illustrated in Figures A I-7-A I-10. In the diamond topology, illustrated in Figure A I-7, there are 4 nodes. Node A and B are in the direct communication range of each other and there are two nodes (R1, R2), located in equal distance from A and B, that can help in the data forwarding process. The distance between nodes A and B is varied from 40 to 125 meters. For each performance evaluation point, the simulation was carried for 110sec. No data is sent for the first 10sec in order to estimate the node-link metrics (in particular the received SNR based on the network layer control packets). Then the data traffic is injected from node A to B and then, after subsequent 2sec, the traffic from node B to A is added. In the 3X3 and 4X4 mesh topologies (Figures A I-8, A I-9) the vertical and horizontal distances between the nodes are 45m. The distances between the neighboring nodes (including the diagonal neighbours) are such that they can communicate with high success rates in order to leverage the coding opportunities. In these topologies the traffic is generated between Node 1 and the opposite corner node (Node 9 in the 3X3 topology and Node 16 in the 4X4 topology). First, Node 1 starts to send data to the opposite corner node and then after 2sec the opposite corner node sends traffic to Node 1. The main objective for testing these two topologies is to verify how the nodes cooperate to forward the data packets and how the coding opportunities are discovered along the way. In the 16-node random topology (Figure A I-10) the nodes were placed in such a way that the flows must travel 4 or 5 hops before reaching its final destination. Two flows are generated. The first from Node 0 to Node 15 and the second, after 2sec, from Node 15 to Node 0. The aggregate end-to-end throughput (network throughput), the ratio of data packets received correctly at the final destination over the number of data packet transmitted by the source (delivery ratio), and the number of transmissions per packet delivery has been measured and used for comparisons. These performance characteristics are analysed in the following subsections.

Network Throughput

The network throughput is defined as the average rate (bytes per second) of all packets received correctly at the final destination nodes. We start from analysing the network throughput results for the diamond topology. Figure 11 shows the network throughput as a function of the A-B distance for NC_BEND, TH, CP, CP_RL, INT, INT-C1 and INT-C2 protocols. The two versions of the INT-C protocol have different SNR threshold values for the neighbor node selection: 11db for INT-C1 and 4db for INT-C2. The first interesting observation is that while the throughput of the INT protocol is higher than any of the individual protocols till 95m, it is lower than in the NC_BEND protocol for larger distances. The reason for this is that above 95m the A-B link is split into two links in the NC_BEND case while in the INT case the A-B link is not split but is in its grey zone (Hollande et al., 2001) and at this distance even the CP protocol fails to maintain a reliable direct link. Consequently the NC_BEND protocol takes advantage of two shorter links since the coding opportunity arises at the relay-node. This feature is illustrated in Figures A I-14 and A I-15 where the distribution of the CP, NC and OR mechanism usage is shown for the NC_BEND and INT protocols.

The second interesting observation is that the throughput of the INT-C protocol is significantly improved above 95m distances when compared with INT and it is also higher than NC_BEND. This is due to two INT-C features. First, the neighbours (to which a node can send packets) are selected based on the link quality (average link SNR). Second, the data rate at which the packets are sent follows the average link SNR as opposed to the instantaneous SNR in RBAR (Hollande et al., 2001). As mentioned before we consider two SNR thresholds for INT-C. When the SNR threshold is set to 11db (INT-C1), there is a significant improvement in terms of the network throughput but the delivery ratio and the number of transmissions per packet delivery (NTPD) are worse than for the SNR threshold set to 4db (INT-C2), although in the INT-C2 case the network throughput is slightly reduced compared to INT-C1. These features can be observed in Figures A I-11, A I-12 and A I-13 showing the performance metrics vs. the A-B distance and in Tables A I-1, A I-2 and A I-3 where the average (over the distance) performance metrics are given. As can be seen from Figure A I-11, the throughput values for the TH, CP and CP_RL protocols are much lower, compared to the INT, INT-C1 and INT-C2 protocols, especially when the A-B distance increases. This is due to the fact that the direct communication in these protocols is being carried out at lower data rates while in the INT, INT-C1, INT-C2 and NC_BEND cases the data packets are sent at higher data rates and using the NC mechanism. The comparison of the network throughput for all considered topologies is given in Table A I-4.

To simplify the presentation, only INT-C2, among the integrated protocol options, is considered for all multihop topologies. The results show that the throughput gains of the INT-C2 protocol are much more pronounced for multi-hop topologies. The biggest one (383% - 446%) are achieved against the traditional hop based protocol, TH, because in this case the nodes send packets without judiciously considering the link quality. When compared with the CP and CP_RL protocols, the gain of the INT-C2 protocol is in the range of (94% - 307%) and (50% - 180%), respectively. Note that the throughput of the CP_RL protocol is higher than the one for the CP protocol and this is due to the relay link creation at the MAC layer and employing opportunistic forwarding. Also, when compared with the NC_BEND protocol the throughput gains of the INT-C2 protocol are significantly higher (50%-78%) than in the diamond topology case. Moreover, it is interesting that the performance of the NC_BEND protocol for the 16-node topology is worse than the one for the CP_RL protocol. This is due to the fact that the CP_RL performs the link creation at the MAC layer while the NC_BEND protocol does not have coordination between network and MAC layer. It should be mentioned that the good performance of the INT-C2 protocol in multi-hop scenarios is also due to the application the CDARM metric that is used to select minimum cost paths.

Delivery Ratio Analysis

The delivery ratio is counted as the ratio of the number of packets received correctly by the destination nodes to the number of packets sent from the origin nodes. In Figure A I-12 the delivery ratio is plotted vs. the A-B distance for the diamond topology case while in Table II the average (over the distance) delivery ratio difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP protocols, respectively, is presented. It can be seen that INT and INT_C2 improve the delivery ratio as compared to any other single protocol. On the other hand, the delivery ratio of the INT-C1 protocol is slightly lower when compared with the NC_BEND case. This comes from the fact that when the SNR threshold is set to 11db, the nodes tend to send data packet at higher rates where the error probability is higher. In Table A I-5, the delivery ratio of the protocols is presented for all considered topologies. As in the case of the throughput metric, the gains of the INT-C2 protocol are significantly more pronounced when compared with the diamond topology case. The reason for this is that the

INT-C2 protocol utilizes the NC mechanism as well as spatial diversity. While NC_BEND outperforms CP, CP_RL and TH protocols in terms of the delivery ratio for the 3X3 mesh topology, its delivery ratio degrades progressively for the 4X4 mesh and 16-node random topologies to the point that it is worse than the CP and CP_RL protocols for the 16-node random topology. Once again this is due to the lack of coordination between the network and MAC layers in the NC_BEND protocol. Moreover, the NC_BEND protocol was designed for single rate transmissions.

Number of transmissions per-packet delivery

The number of transmission per-packet delivery, NTPD, is defined as the ratio of the number of packet transmissions made by the source and the intermediate nodes to the number of packets successfully received by the final destination nodes. NTPD for the diamond topology is plotted in Figure A I-13 vs. the A-B distance and the averages, over the distance, are given in Table III. The results show that NTDP for the INT, INT_C2 protocols is smaller when compared with the TH, CP_RL, NC_BEND and INT_C1 protocols. CP protocol makes less transmission as compared to INT_C1, this is because in INT_C1 the neighbor selection threshold was too high and at 90m, the link is no longer direct, it being spitted in two hops. Table VI presents NTDP for all considered topologies. For the 3X3 mesh topology, INT-C2 gives NTDP = 1.93, which is the lowest value among all the protocols. This is caused by the fact that in this case the data packets travel via two hops and employs coding of the data packets at the intermediate nodes or the relay nodes (2, 4, 5 or 6, 8). In the NC_BEND case we have NTDP = 2.74, which implies that the packets travel via more than two hops and this is due to the lack of coordination between the network and MAC layers. As the number of hops increases for the 4X4 mesh and 16-node random topologies, the gap between NTDP for INT-C2 and NC_BEND increases. Concerning the CP_RL protocols, only for the 16-node random topology the NTDP value for the INT-C2 protocol is slightly higher compared with the CP_RL protocol. This is due to the fact that the CP_RL protocol creates longer links and applies opportunistic forwarding, while in INT-C2 the links are selected based on the average received SNR threshold, so the packets travel through more hops compared to the CP_RL.

Note that while the packets travel via more nodes in the INT-C2 protocol, the INT-C2 throughput is still higher than in the CP_RL. This is because in the INT-C2 case the data rate is related to the link quality and the path is selected based on the CDARM metric.

Distribution of CP, NC, OR mechanisms usage in INT and INT-C2

In this section we analyse distribution of the CP, NC and OR mechanisms usage in the INT and INT-C2 cases. Figures A I-15 and A I-16 show the distribution of the CP, NC, and OR mechanisms usage in the INT and INT_C2 protocols for the diamond topology as a function of the A-B distance. The figures indicate that, as the A-B distance grows, the NC and OR mechanisms become more active in the INT_C2 protocol when compared to the INT protocol. Figure A I-17 shows average fraction of the CP, NC and OR usage in the integrated protocols. The CP, NC, and OR mechanisms usage distributions in INT-C2 for all considered topologies are presented in Table A I-7. For the diamond topology, the share of the CP mechanism is highest, although the shares of NC and OR mechanisms increase gradually as the A-B distance increases. It is interesting to note that in the 3X3 mesh topology the NC and OR mechanisms are almost equally active but the OR mechanism becomes more active as the number of hops travelled by packets grows.

V. Conclusion

In this paper we proposed an approach for integration of the network coding, spatial diversity and opportunistic routing/forwarding mechanisms that leverage the broadcast nature of the wireless links. In particular we proposed a cross-layer based integration of the mentioned three techniques to accumulate their potential gains using the same network protocol stack in wireless mesh networks. The proposed integration approach is based on a new metric CDARM (Coding opportunity and Data rate Aware Routing Metric) used for the route selection and a method for creating relay link at the MAC layer. Based on the system level simulation, our results demonstrate that the integration can improve significantly the performance in terms of the network throughput, data delivery ratio and number of transmission per packet delivery. Moreover the results show that the integrated protocol outperforms any single protocol.

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Table A I-1 Average network throughput difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP, respectively, for diamond topology

Through put Difference	**TH**	**NC_ BEND**	**CP**	**CP_ RL**
INT	21	13	14	15
INT-C1	32	23	24	25
INT-C2	25	16	17	18

Table A I-2 Average delivery ratio difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP, respectively, for diamond topology

Delivery	**TH**	**NC_**	**CP**	**CP_**

Ratio		BEND		RL
INT	6.5	1.5	6.4	12.9
INT-C1	2.8	-1.85	2.9	9.1
INT-C2	5.1	0.19	4.9	11.2

Table A I-3 Average NTPD difference (%) between INT, INT-C1, INT-C2 and TR, NC_BEND, CP, respectively, for diamond topology.

NTPD	TH	NC_ BEND	CP	CP_ RL
INT	-14	-6.3	1.0	-14
INT-C1	-11	-2.0	6.8	-10.3
INT-C2	-18	-9.7	-3.2	-18

Table A I-4 Network throughput for all topologies

Topology	Protocol	Network Throughput (Kbps)X1e+003
Diamond	TH	5.14
	CP	5.49
	CP_RL	5.44
	NC_BEND	5.53
	INT	6.24
	INT-C1	6.79
	INT-C2	6.43
3X3	TH	1.14
	CP	1.36
	CP_RL	1.98
	NC_BEND	3.68
	INT-C2	5.54
4X4	TH	0.29
	CP	0.49
	CP_RL	0.89
	NC_BEND	1.16

	INT-C2	1.80
16-node	TH	0.39
	CP	0.69
	CP_RL	0.90
	NC_BEND	0.75
	INT-C2	1.34

16-node	TH	0.10
	CP	0.23
	CP_RL	0.31
	NC_BEND	0.19
	INT-C2	0.44

Table A I-5 Delivery ratio for all topologies

Topology	**Protocol**	**Delivery Ratio**
Diamond	TH	0.94
	CP	0.95
	CP_RL	0.90
	NC_BEND	0.97
	INT	0.99
	INT-C1	0.96
	INT-C2	0.98
3X3	TH	0.34
	CP	0.50
	CP_RL	0.63
	NC_BEND	0.89
	INT-C2	0.97
4X4	TH	0.11
	CP	0.20
	CP_RL	0.41
	NC_BEND	0.33
	INT-C2	0.51

Table A I- 6 Number of transmissions per packet delivery (NTPD) for different topologies

Topology	**Protocol**	**NTPD**
Diamond	TH	1.99
	CP	1.7
	CP_RL	2.0
	NC_BEND	1.77
	INT	1.68
	INT-C1	1.78
	INT-C2	1.62
3X3	TH	7.03
	CP	3.94
	CP_RL	4.06
	NC_BEND	2.74
	INT-C2	1.93
4X4	TH	22.44
	CP	11.6
	CP_RL	7.86
	NC_BEND	8.40
	INT-C2	6.0

16-node	TH	14.84
	CP	8.8
	CP_RL	7.98
	NC_BEND	10.99
	INT-C2	8.15

Table A I-7 CP, NC, and OR usage distributions in INT-C2 for all topologies

Topology	**CP**	**NC**	**OR**
Diamond	75	8	17
3X3	54	22	24
4X4	58	8	34
16-node	64	8	28

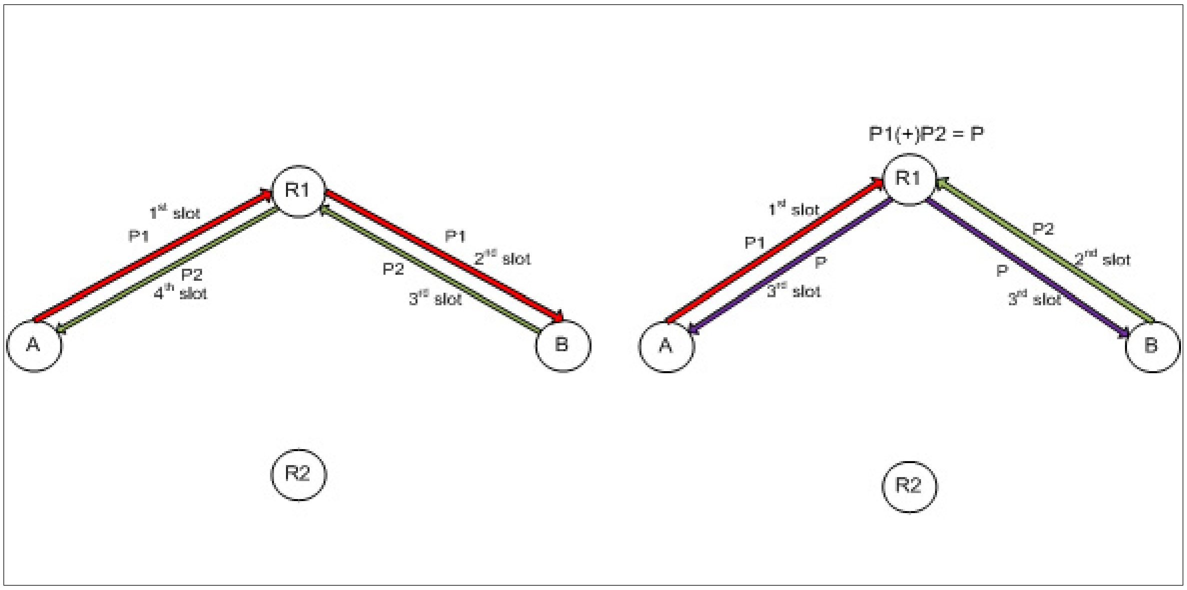

Figure A I-1 Network coding illustration

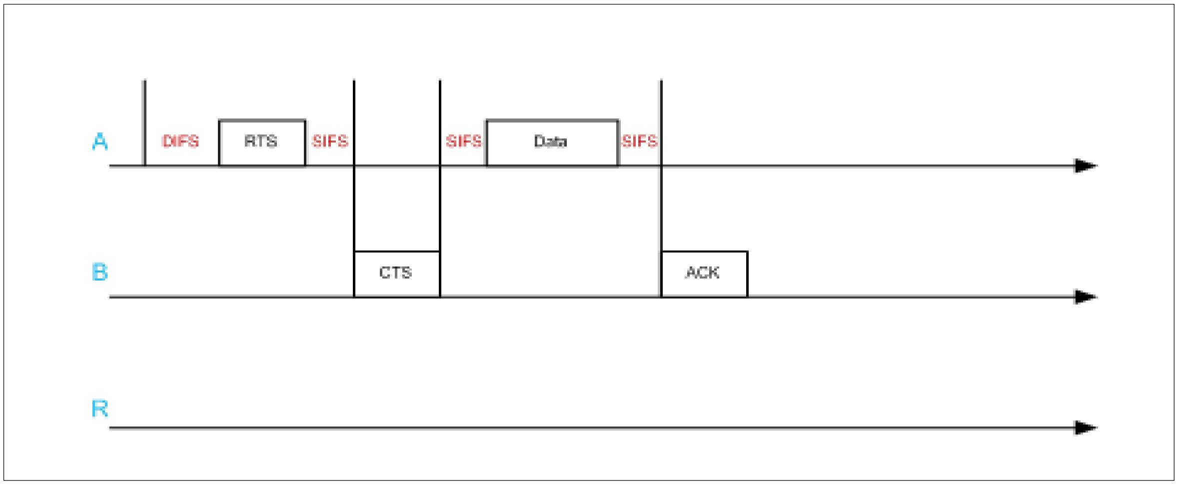

Figure A I-2a Timing diagram for Cooperative protocol (direct transmissions)

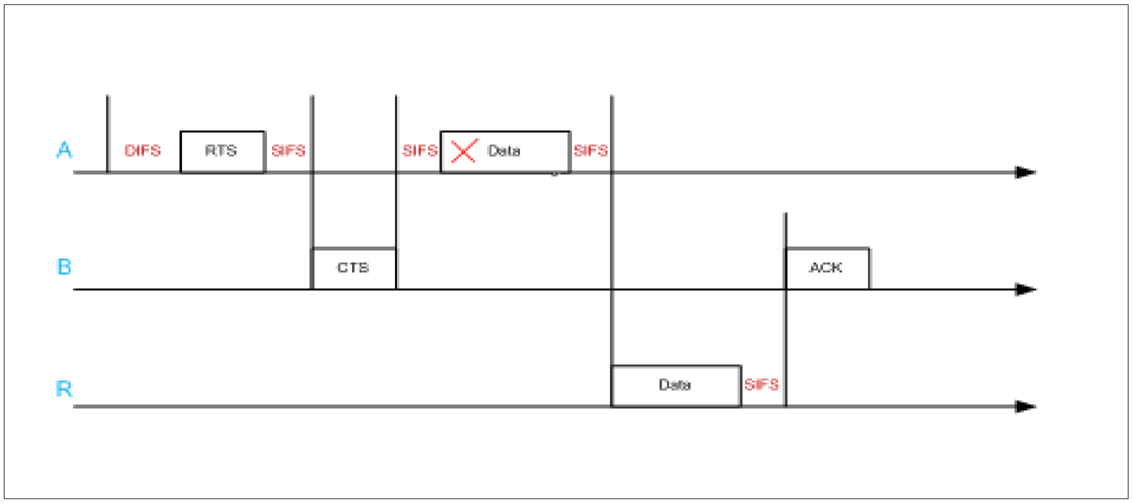

Figure A I-2b Timing diagram for Cooperative protocol (relayed transmissions)

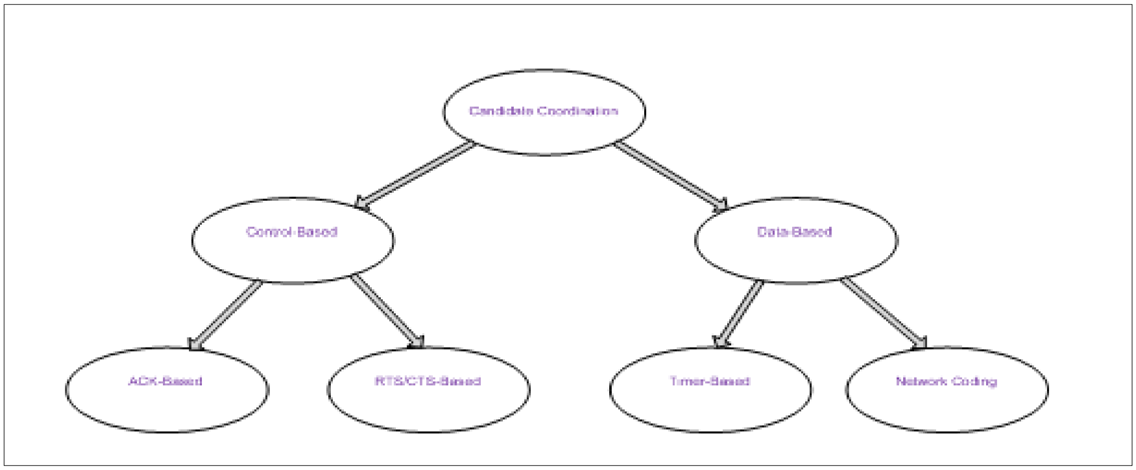

Figure A I-3 Classifications of OR protocols based on Candidate coordination

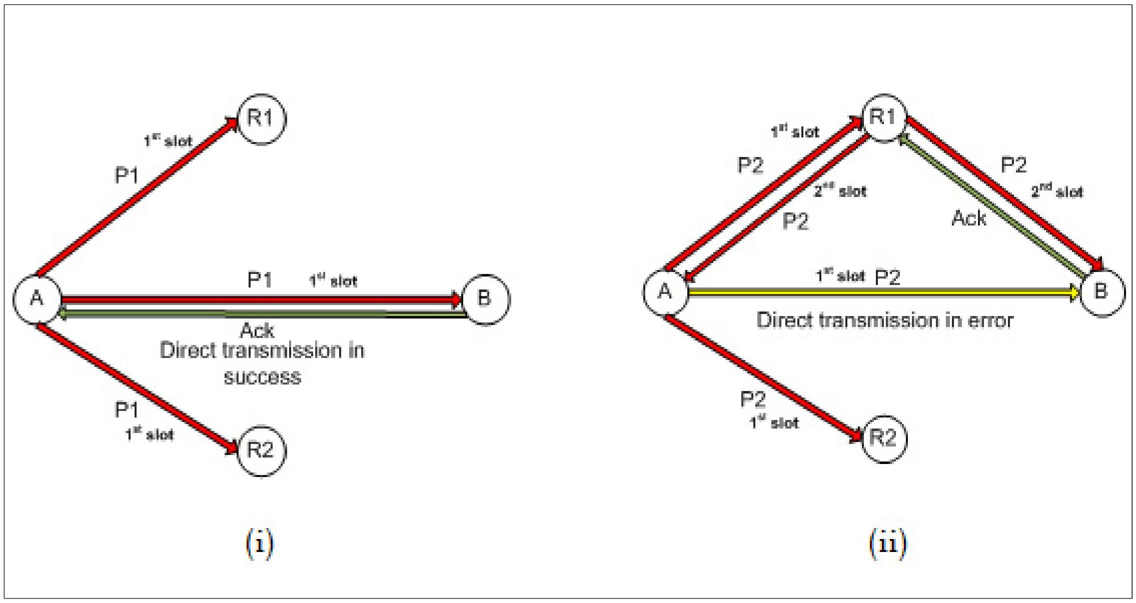

Figure A I-4a Illustrations of Cooperative protocol integration

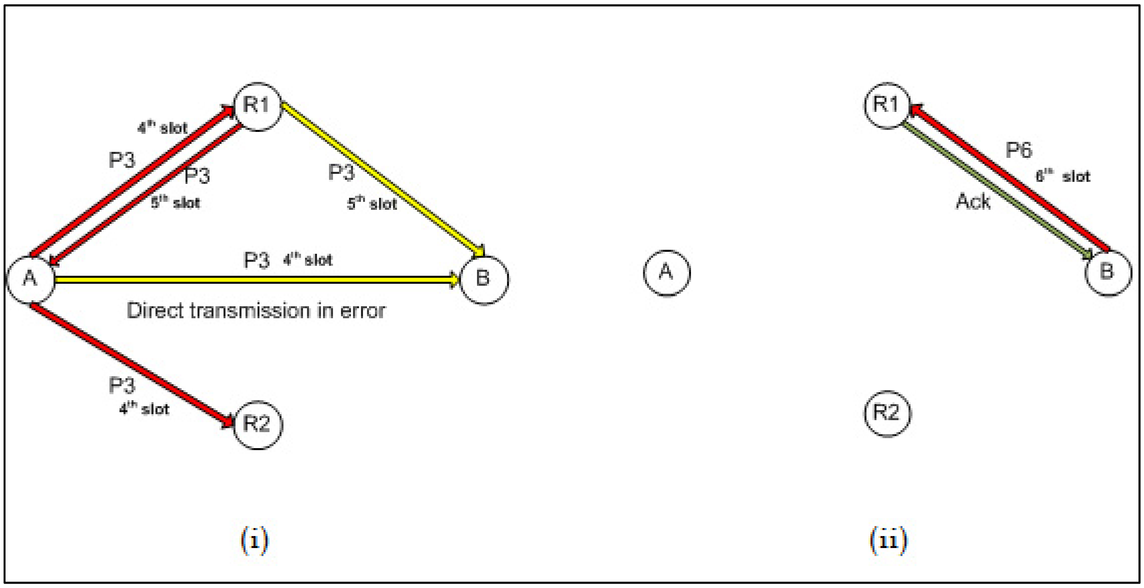

Figure A I-4b Illustrations of Cooperative protocol integration
(relay intervention)

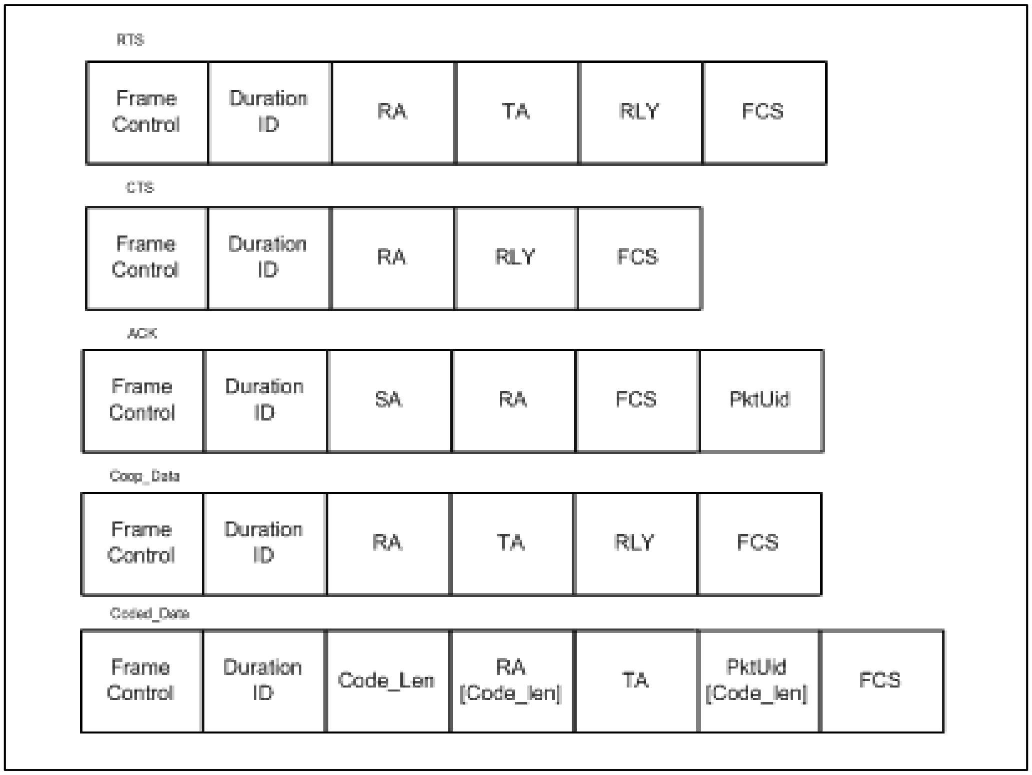

Figure A I-5 Modified MAC header for Integrated Protocol

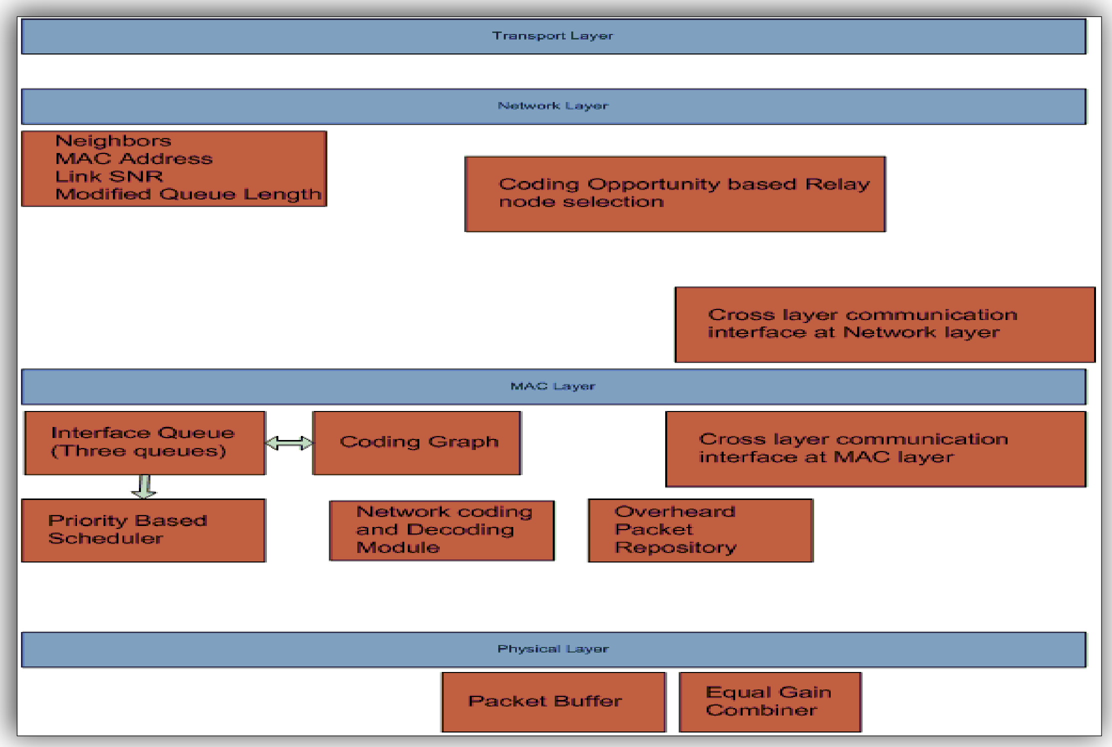

Figure A I-6 The integrated protocol architecture

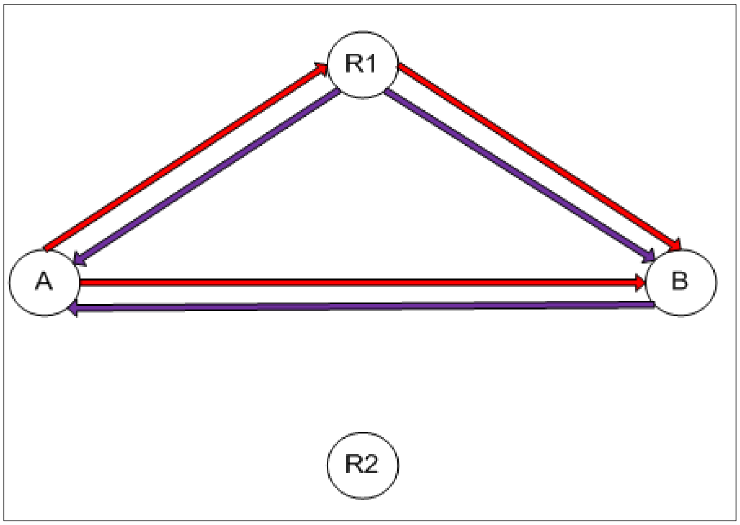

Figure A I-7 Diamond topology

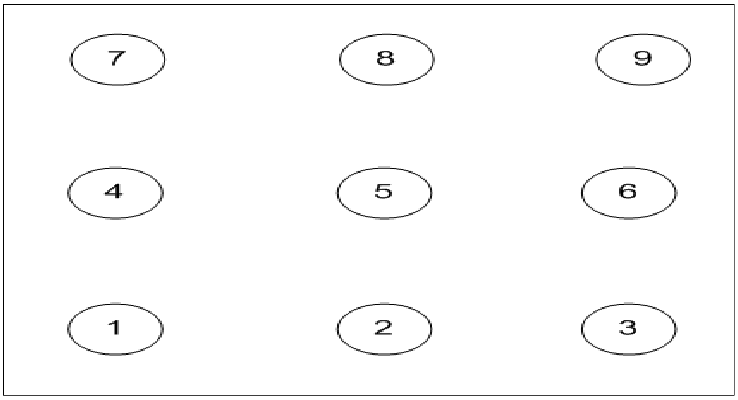

Figure A I-8 3X3 mesh topology

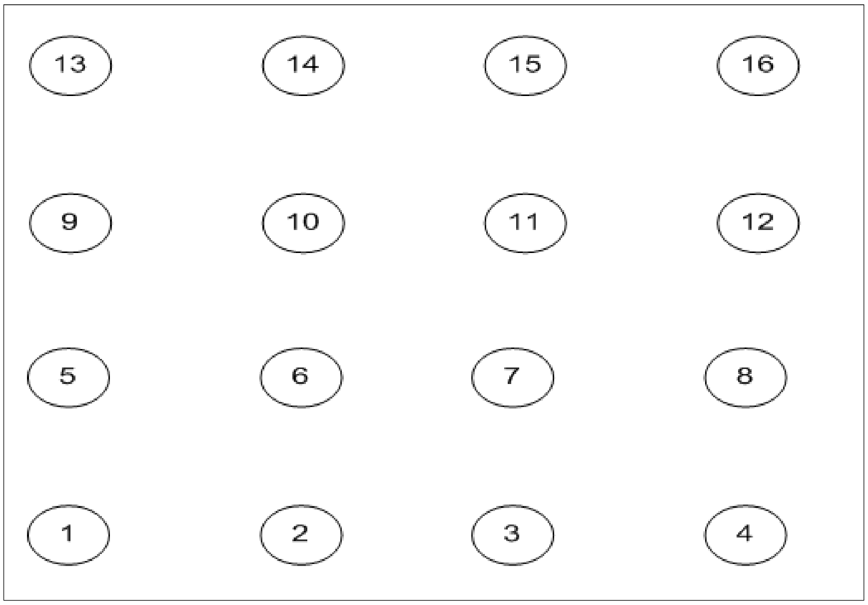

Figure A I-9 4X4 mesh topology

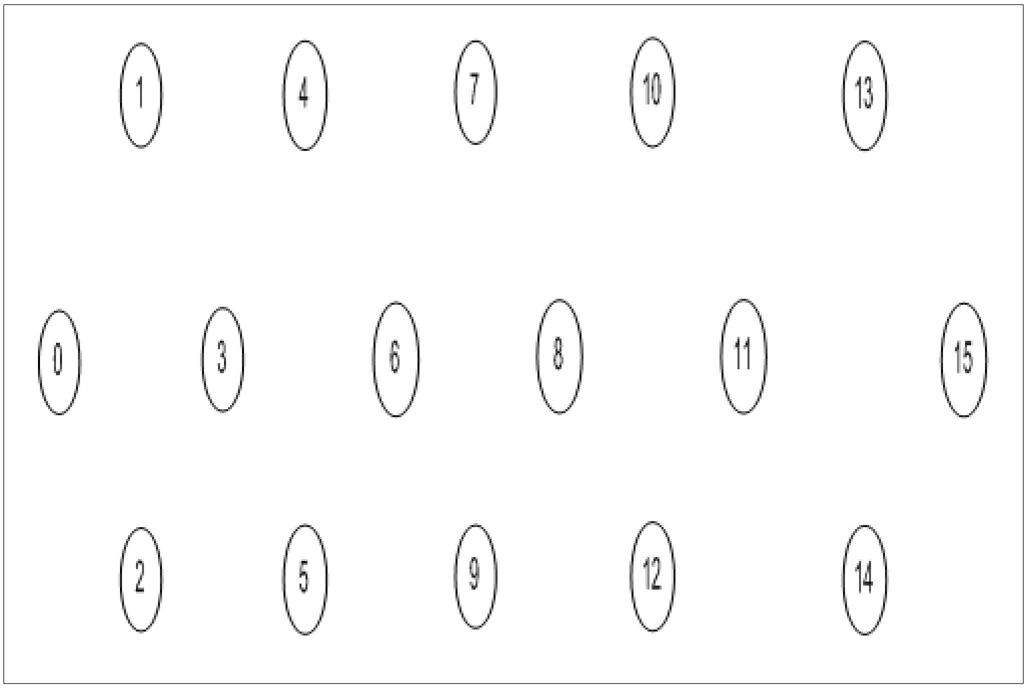

Figure A I-10 16-node random topology

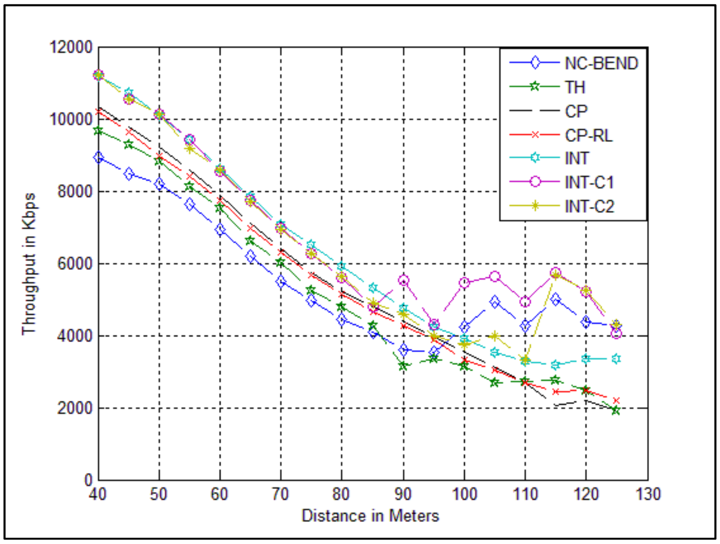

Figure A I-11 Network throughput for Diamond Topology vs. A-B distance

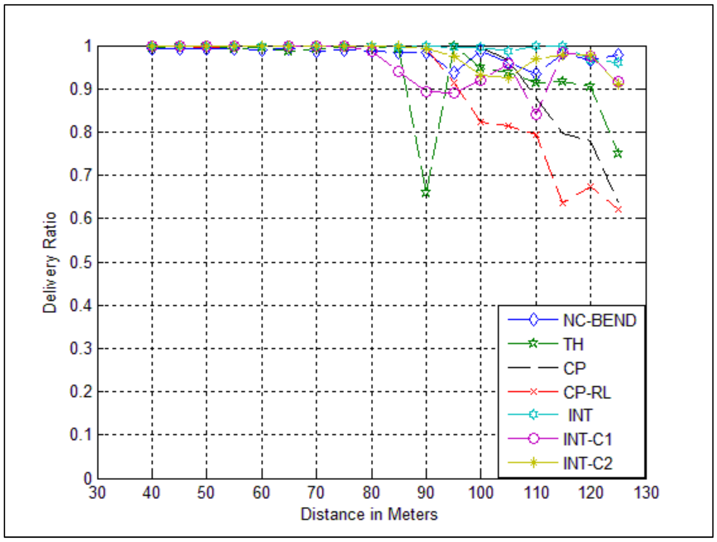

Figure A I-12 Delivery Ratio for Diamond Topology vs. A-B distance

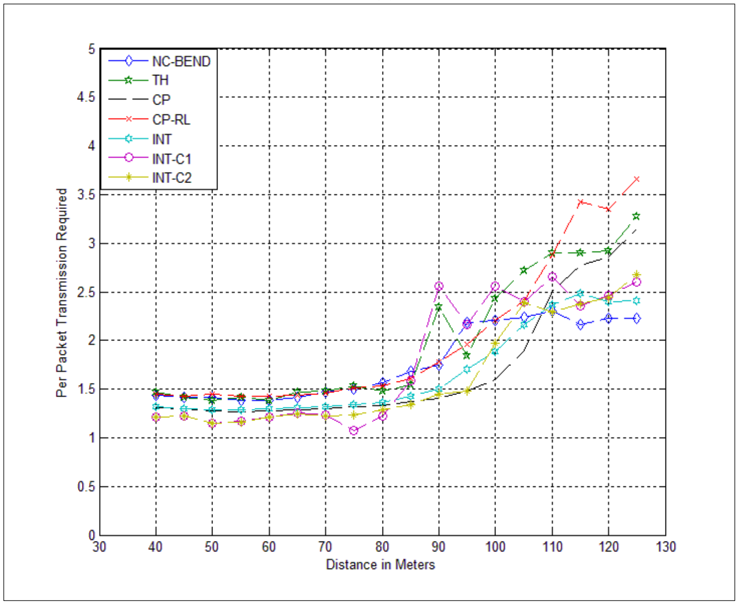

Figure A I-13 Number of transmissions per packet delivery (NTPD) vs. A-B distance

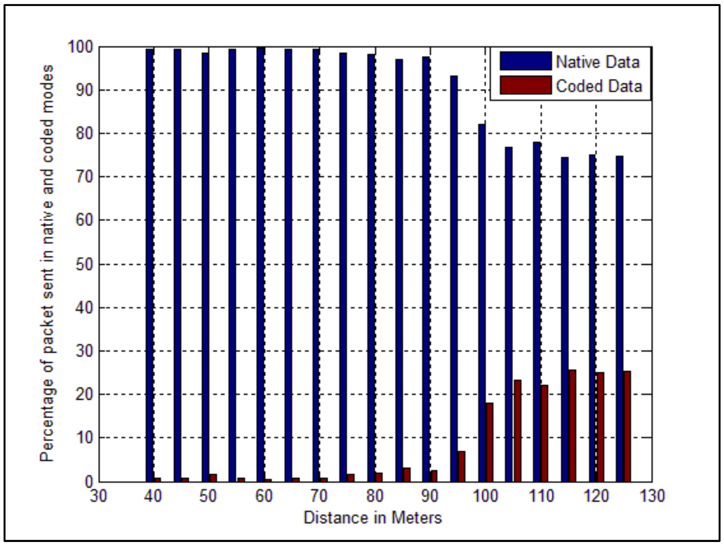

Figure A I-14 Fraction of the packets sent in native and coded mode in NC_BEND vs. A-B distance

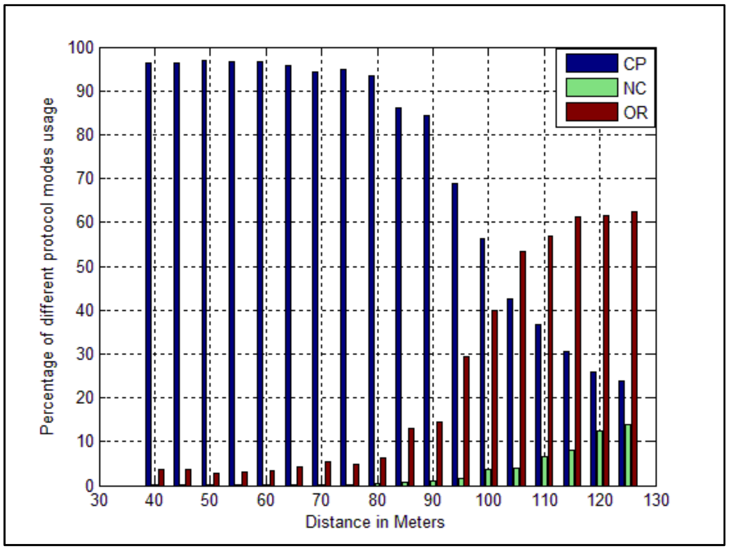

Figure A I-15: Fraction of the CP, NC and OR usage in INT-C2 vs A-B distance

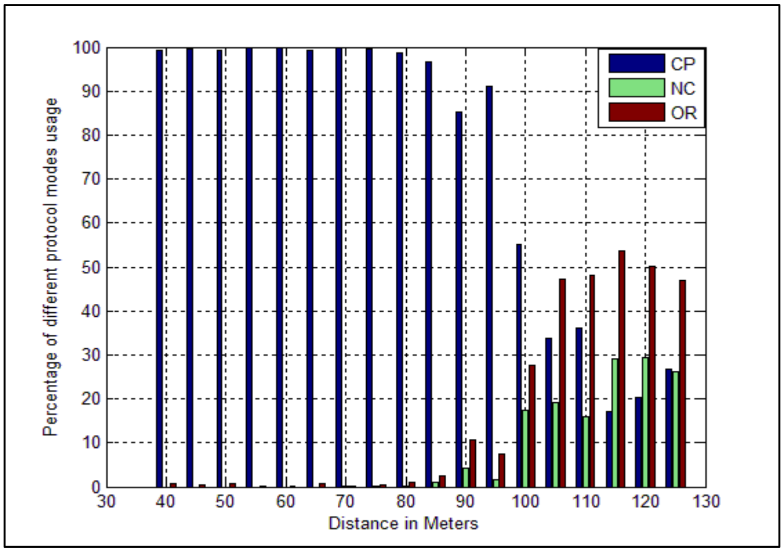

Figure A I-16: Fraction of CP, NC and OR usage in INT-C2 vs A-B distance

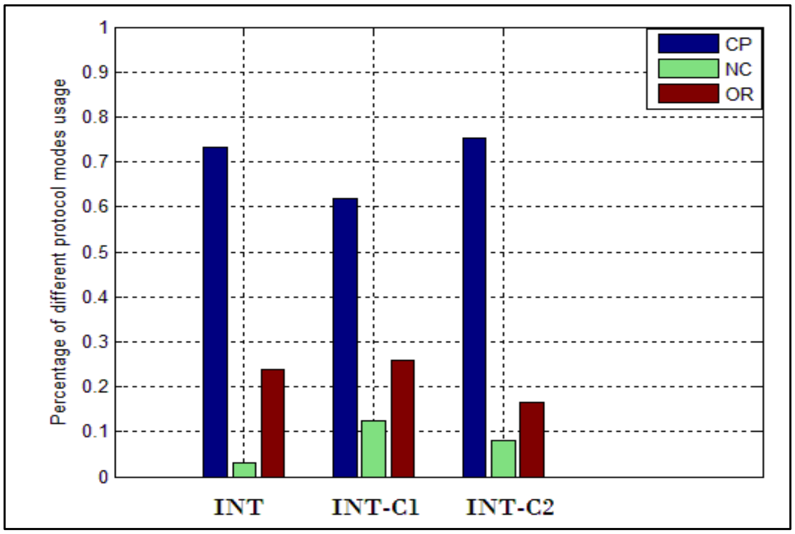

Figure A I-17 Average fraction of the CP, NC and OR usage in the integrated protocols for diamond topology

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