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Radio Resource Management Strategies for Wireless Mesh Networks

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To my parents Tomasz & Genowefa,

To my beloved friend Cebula,

And to Piotr.

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Abstract

This study is to evaluate the impact of key network and node parameters on the performance of Wireless Mesh Network implemented over the IEEE 802.11a system. Main studies have been conducted using hexagonal topology network model. Two radio channel usage evaluation functions are analysed. Simulations using OPNET software have been run revealing following results. Using freespace propagation model in a network that consist of 31 nodes, where 7 orthogonal channels are utilised it is possible to reach connectivity only with the transmission power of 1000mW. In any case where the uplink traffic is scheduled it is beneficial to use CSMA/CA with RTS-CTS mechanism in the multichannel network. The larger the size of area that node takes into account when evaluating the channel usage is the more advantageous in terms of performance the network is but less advantageous in terms of stability. When only the downlink traffic scenario is considered the Less Used usage function is better for less than 4 channels in 2 ring scenario and less than 7 channels in 3 ring scenario. In uplink traffic case the Weighted Less Used usage function is performing better for all number of channels.

Keywords

Wireless Mesh Networks, WLANs, Radio Resource Management, Radio Channel Assignment

Streszczenie

Praca ta ma na celu analizę wpływu kluczowych parametrów sieci oraz jej węzłów na wydajność Sieci Bezprzewodowej Typu Mesh zaimplementowanej używając systemu IEEE 802.11a. Sieć została zaimplementowana wykorzystując heksagonalną topologię. Dwie funkcje określające wykorzystanie kanałów radiowych są zanalizowane. Grupa symulacji została przeprowadzona używając oprogramowania OPNET i zaowocowała następującymi wynikami. Używając modelu propagacyjnego wolnej przestrzeni w 4-ro pierścieniowej sieci, gdzie węzły wykorzystują 7 ortogonalnych kanałów, możliwe jest uzyskanie jakiegokolwiek wydajności promieniując moc 1000mW. Gdziekolwiek ruch pakietów kierowany jest w stronę bramy do Internetu używając mechanizmu RTS-CTS ustanawiania połączenia otrzymane są lepsze niż bez tego mechanizmu. Jedynie, gdy ruch pakietów kierowany jest od bramy do węzłów nie ma potrzeby wykorzystywać mechanizmu RTS-CTS w wielokanałowej sieci. Wzrost wielkości obszaru, jaki węzły biorą pod uwagę podczas analizy wykorzystania kanałów radiowych ma pozytywny wpływ na wydajność sieci, lecz negatywny na jej stabilność. Gdy ruch tylko od bramy do węzłów jest brany pod uwagę funkcja Ilość Węzłów pokazuje lepszą wydajność dla mniej niż 4 kanałów w sieci 2-u pierścieniowej oraz dla mniej niż 7 kanałów w sieci 3-ój pierścieniowej. W przypadku ruchu od węzłów do sieci funkcja Wazona Ilość Kanałów ma lepszą wydajność przy wykorzystaniu jakiegokolwiek ilość kanałów radiowych. Teoretyczne maksimum przy ruchu od węzłów do bramy nie jest osiągnięte ze względu na naturę mechanizmu RTS-CTS.

Słowa-klucze

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List of Acronyms

ACK	Acknowledgement
AI	Access Interface
AP	Access Point
ARP	Address Resolution Protocol
BER	Bit Error Rate
bps	Bits Per Second
BSS	Basic Service Set
CA	Collision Avoidance
CC	Common Channel
CCC	Common Control Channel protocol
CCK	Complementary Code Keying
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CUT	Channel Usage Table
CW	Contention Window
DCA	Dynamic Channel Allocation
DCF	Distributed Coordination Function
DI	Dynamic Interface
DIFS	Distributed Coordination Function interframe Space
DL	Downlink
Down-NIC	Downlink Network Interface Card
DS	Distribution System
EIFS	Extended Interframe Space
ESS	Extended Service Set
ETSI	European Telecommunications Standard Institute
FEC	Forward Error Correction
FSM	Finite State Machine
GHz	Giga Hertz
HMCP	Hybrid Multichannel Protocol
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IFS	Interframe Space
IP	Internet Protocol
ISP	Internet Service Provider
LACA	Load Aware Channel Assignment
LAN	Local Area Network

LLC	Logical Link Control
LOS	Line Of Sight
LU	Less Used
MAC	Medium Access Control
MAP	Mesh Access Point
Mbps	Mega Bits per Second
MesTIC	Mesh based Traffic and Interfere aware Channel assignment scheme
MIMO	Multiple Input Multiple Output
ML	Mesh Link
MP	Mesh Point
M-R	Multi-Radio
MRMC	Multi Radio Multi Channel
MSDU	Mac Service Data Unit
MT	Mesh Traffic channel
NIC	Network Interface Card
NP	Nondeterministic Polynomial time
NT	Neighbour Table
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditures
OSI	Open System Interconnection
PCF	Point Coordination Function
PCL	Preferable Channel List
PDA	Personal Digital Assistant
PER	Packet Error Rate
PHY	Physical
PIFS	Point Coordination Function interframe Space
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependent
RCA	Radio Channel Allocation algorithm
RTS	Request To Send
SDU	Service Data Unit
SI	Static Interface
SIFS	Short Interframe Space
SINR	Signal to Interference Noise Ratio
S-R	Single Radio
SRMC	Single Radio Multi Channel
STA	Station
STD	State Diagram Transition
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access

TML	Theoretical Maximum Load
Tx	Transmission
TxOP	Transmit Opportunity
UF	Usage Function
UL	Uplink
Up-NIC	Uplink Network Interface Card
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
WLU	Weighted Less Used
WMN	Wireless Mesh Networks

List of Symbols

τ_{e2e}	End-to-End Delay
τ_{ACK}	Delay of Acknowledgment Packet
τ_{BO}	Delay of Backoff Period
τ_{CTS}	Delay of Clear To Send Packet
τ_{DATA}	Delay of Transmitting The Data
τ_{DIFS}	Delay of DIFS
τ_{RTS}	Delay of Request To Send packet
τ_{SIFS}	Delay of SIFS
τ_{total}	Total delay
τ_{rx}	Time of receiving the packet
τ_{tx}	Time of transmitting the packet
τ_{e2e}^{av}	Average End-to-End Delay
τ_{max}	Maximum Voice Packet Delay
τ_{static}	Time between static interface channel change
$\tau_{dynamic}$	Time between dynamic interface channel change
ΔL	Log-normal shadowing variable
ε	Coefficient of the interference
A	Activity
a_{pd}	Average Power Decay
B	Bandwidth
d	Distance between transmitter and receiver
d_0	Reference distance
$d_{i,t}$	Theoretical Interference Range
$d_{i,o}$	Interference Range in Opnet
d_{n2i}	Node to Interferer distance
d_{n2n}	Node to Node distance
$d_{ohn-ohn}$	Distance between One Hop Neighbour and the other One Hop Neighbour of a particular node
d_{tx}	Transmission Range
$d_{tx,max}$	Maximum Successful Transmission Range
f	Frequency
G_{tx}	Transmission Gain
G_{rx}	Reception Gain
L_p	Path Loss
L_{p0}	Reference Path Loss

M_r	Receiving Mesh Node
M_t	Transmitting Mesh Node
N_{ch}	Number of Channels
N_{ch_ort}	Number of Orthogonal Channels
N_{h_max}	Maximum Number of Hops to the gateway
N_{int}	Number of Interfaces
N_{h_gw}	Number of hops to the gateway
N_n	Total Number of Nodes
N_{n_act}	Number of active nodes
N_{n_lm}	Number of Last Mile Nodes
N_{ohn}	Number of One Hop Neighbours
N_r	Number of Ring
P_I	Power Level of Interference
P_{min}	Receiver Sensitivity
P_N	Power Level of Noise
P_{N_0}	Power of Average White Gaussian Noise
P_{rx}	Power Received
P_S	Power Level of Signal
P_{tx}	Transmission Power
R	Data Rate
R_{app_maxmin}	Maxmin Theoretical Traffic Rate
R_{app}^{gw}	Gateway Aggregated Application data rate
R_{app_gen}	Application Data Rate Generated
r_{app_gen}	Application Data Rate generation ratio
$r_{SINR_{min}}$	Minimum Power of Signal to Interference Noise Ratio
R_{t_app}	Theoretical Application Data Rate
R_{Op_mac}	Application Data Rate without “artificial” overhead
R_{Op_bias}	Application Data Rate with “artificial” overhead
S_p	Packet Size
S_{p_oh}	Packet Size with normal overhead
S_{PLCP}	Packet Size with of the “artificial” overhead added to the packet by Opnet
T_{hello}	Time between broadcasting of Hello Packet
U_{T_LU}	Usage of a channel counted by Less Used Function
U_{T_WLU}	Usage of a channel counted by Weighted Less Used Function
W	Weight
X_m^{Cc}	Neighbourhood of node m with channel c in use

List of Software

Microsoft Excel 2007	It is an electronic spreadsheet program. It is useful to record, to analyse, and to show information. It is also helpful in computing formulas.
Microsoft Office Visio 2007	Visio is a tool for creating all kind of business diagrams, network layouts, storyboards and site flows, software entity relationship diagram, etc.
OPNET Modeler 15.0	It is a Discrete Event Simulator, which allows the implementation of models using the library of object already done. Several technologies, protocols, and devices, are available to analyse various kind of networks. Several outputs are available to analyse the results.

Chapter One

Introduction

In this chapter a brief overview of thesis is given. Motivation, state of the art, and the goals of this work are presented. The thesis structure is provided at the end of the chapter.

In recent years the internet connectivity became an asset that is of value for many people that need an easy access to information. Every cable network is difficult to build as high expenditures must be made to lay down the infrastructure. The alternative is a wireless network that allows easy access for users, who need only the wireless adapter to connect to the network. Normally base stations still need to be interconnected by physical cable interface. In this work the base stations are connected by wireless links with other surrounding stations. Nodes form a self-organising and self-healing network which is called Wireless Mesh Network (WMN) [1].

As each Internet Service Provider link is costly there is a possibility to give access to the internet service by nodes relaying the packets for other nodes in the network. This is called multihop network as the packet from the source node, hop a few times between the nodes to reach the destination node. The destination node with connection to the internet is called gateway node (GW). As in many cases users do not fully utilise the capacity of a link that they purchased, the multihop network may serve for many users, using only one ISP link. WMN is a good example of multihop network.

Many systems may be used to build the WMN, depending on the demand for capacity, coverage areas and costs of deployment. One of the most popular and reliable wireless communications standards on the market is IEEE 802.11 [2]. It has been developed by IEEE 802.11 Working Group, formed in September 1990. The aim was to create Wireless Local Area Network (WLAN) standard that would operate in the industrial, scientific and medical frequency ranges. The first standard 802.11 has been released in 1997. After first release, the next 802.11b standard, supporting 11Mbps extension was developed. It supports data rates up to 54Mbps and the transmission signal is in regulated frequency spectrum band around 5GHz. In 2002 and 2003, WLAN products supporting a new standard called 802.11g came to the market, that attempt to combine the best from 802.11a and 802.11b. It supports data rate up to 54Mbps and use the 2.4 GHz frequency to increase the coverage area. However when using 802.11a standard it is possible to use higher transmission power than when using 802.11g standard to compensate the greater absorption of power in 5GHz band. Higher power allows to achieve better coverage in LOS conditions. That is why, for this work 802.11a is chosen.

Normally 802.11 Access Points (APs) usually operate in infrastructure mode, using central Access Point to relay all of the traffic in the network. APs provide access services for Client nodes that are also able to connect with each other through the AP. Normally APs are interconnected with wired connections that provide access to the Internet. It is possible however to interconnect APs via wireless links and form Mesh Access Points (MAPs) that deliver the packets from a source to destination by multihop transmission. 802.11 systems as well as many other wireless communication systems can be successfully used to form a WMN.

WMNs allow easy increase of connectivity area at low cost as the infrastructure expenditures are lower than when deploying cable network. For example there is no need to neither lay down the cables nor make any construction work. Simple configuration is another advantage of WMN. As it is considered as ad-hoc network it can self-organise and self-heal by the nodes in the network automatically establishing and maintaining connectivity among themselves. Potential applications of

WMN networks are listed in the following chapter.

When deploying WMN a few radio interfaces are used, which allow simultaneous reception and transmission of a signal in this way increasing the performance of the network. To allow this the interfaces need to transmit on orthogonal channels. The 802.11a system used in this work allows using 11 orthogonal channels. Taking into consideration that usually in the WMN network there are many nodes, it is possible to transmit on all of those channels simultaneously increasing the capacity seriously. The challenge is to assign the same channels within the largest distance between them.

The key issue when using WMNs is radio resources usage. As usually the number of available channels to choose from is lower than the number of nodes to assign the channels to, the interferences are present. The node used in this work utilises two radio interfaces, which usually use orthogonal channels. The Radio Channel Allocation (RCA) algorithm assigns the channels to one of the radio interfaces and the choice of assigned channel influence the performance greatly.

The channel distribution among the network and its impact on performance is studied in this work. The key factors influencing the choice of the channel are being analysed, together with many parameters influencing the topology of the network and the nature of multihop transmission. The goal of the thesis is to evaluate the RCA algorithm developed by other author. It is done by conducting studies to define the parameters of RCA, nodes and network that augment the data rates. The achieved delays and packet losses are used as quality indicators. The influence on performance of the network of key network and node parameters are analysed:

- Node Transmission Power,
- Radio Access Scheme,
- Number of Neighbours,
- Number of Ring, where is a group of nodes that is within the same distance from the gateway in terms of hop count,
- Number of Neighbours in the area where the channel usage is evaluated,
- Number of Channels, both in uplink and downlink case,
- Direction of Proportion of the uplink/downlink traffic,
- Number of Active Nodes in the Network.

Two RCA algorithms are compared during this study. The first one assigns the channel to static interface choosing the one that is used the least in the closest neighbourhood of the node. The latter one does the same and also weights the channel importance according to distance of the node using the channel to the gateway, with the GW's channel being the most important and thus the least used.

To simulate the network performance OPNET Modeler 15.0A [3] was used. The nodes model as well as Radio Channel Allocation Algorithm were derived from the Lúcio Studer Ferreira Ph.D. work [4]. It has been developed on the basis of a few other channel allocation algorithms which are being described in detail in Chapter 2.

The simulations were conducted using two scenarios, the Chain Scenario and the Ring Scenario. The first one is useful for understanding the nature of multihop transmission combined with multichannel

interfaces usage. The second scenario is the main scenario used for study, where the impact of the key parameters of node, network and RCA is analysed on the performance of the network. In the Ring scenario, three topologies are implemented: 2, 3 and 4 Rings. The scenarios foreseen as target of this work are rural scenarios, where no major obstacles are present and freespace propagation model can be used.

This thesis is composed of 5 chapters.

- Chapter 1 – Introduction
- Chapter 2 – State of the art, where overview of Wireless Mesh Networks is given, explaining the main concepts. It is followed with a WLAN standard summary with its aspects relevant for the work. The chapter is finalised with a description of a few Radio Channel Assignment (RCA) algorithms that were the base for RCA algorithm under study in this work.
- Chapter 3 – Algorithm and simulator description, where network and node model is presented at first. Later the propagation model used in simulator is described. RCA algorithm developed for the WMNs is presented next, followed by OPNET simulator software description. The chapter finishes with presentation of implementation issues of RCA in OPNET software.
- Chapter 4 – Analysis of results, the description of scenarios is given in detail at the beginning of a chapter. Later the results from Chain scenario are presented. The last section of the chapter is Ring scenario results.
- Chapter 5 – Conclusions, summarises the work and gives some ideas for future work.
- Annexes – Is an additional chapter where results from studies that did not fit inside the work are presented, together with some additional information.

Chapter Two

State Of The Art

This chapter provides overview of Wireless Mesh Networks, WLANs and the usage of WLANs in the WMNs. At the end of the chapter performance parameters are defined.

2.1 The Wireless Mesh Networks

The idea underlying the WMNs is to enable nodes of the network to self-configure and self-maintain the network in the mesh topology. If a packet is to be sent through the network it will hop between the nodes. WMNs consist of two types of nodes: *mesh routers* and *mesh clients*. Mesh routers above conventional gateway/repeater functions contain additional routing functions to support mesh networking.

The architecture of WMNs can be classified into three main groups based on the functionality of the nodes [1]. *Infrastructure/Backbone WMNs* consist of mesh routers, some providing gateway services that form an infrastructure for the clients who connect to them. The mesh routers form self-configuring, self-healing links among themselves, just like in the wired mesh network. In the *Client WMNs* networking type peer-to-peer networking among client devices is provided. Client nodes provide end to end connectivity by performing routing and configuration functionalities among themselves. Gateway and bridge functions do not exist in these nodes. The *Hybrid WMNs* architecture which is the most applicable one is combination of the two described before. Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. The described topology is presented on Figure 2.1.

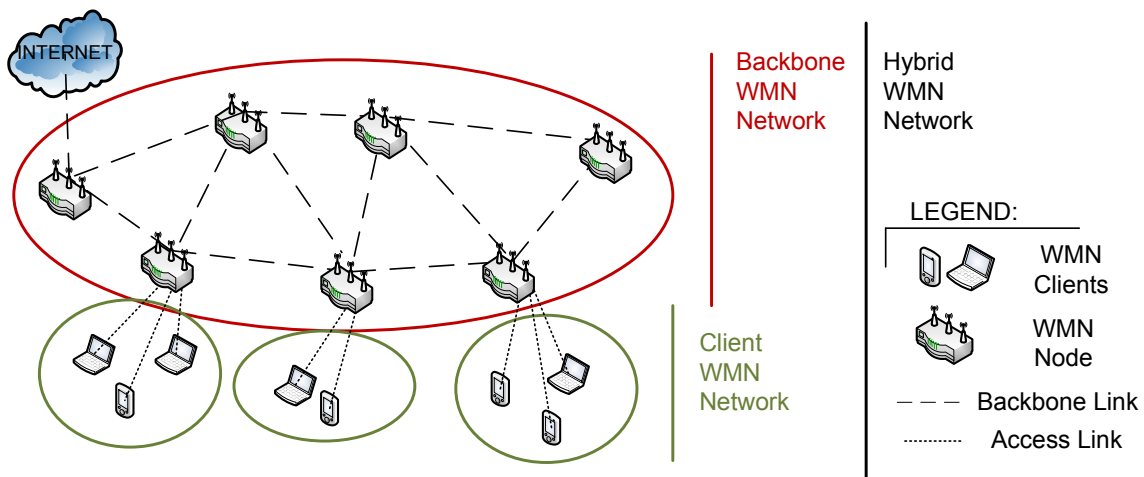


Figure 2.1 - Wireless Mesh Network Architecture (extracted from [5]).

Two basic concepts of management are present in WMNs. Centralized management [6] is a concept where the main server with complete traffic information about every node takes the responsibility for fair distributing the load heading to the gateways. It needs to gather information from every node to create the holistic view on network. Afterwards it distributes the available bandwidth to the nodes according to its demands. As it is NP complete problem, where many of options must be verified, plenty of computational power is needed. Distributed management, which is another management concept, on the other hand requires every node to manage itself. Nodes need to be aware of other nodes traffic situation and cooperate to achieve fair traffic distribution. This features four major characteristic of WMN [7]: self-organisation, self-heal, self-optimize and self-protect. The problems

named are: random distribution of nodes what makes network irregular, error prone wireless transmission medium and limited batter resources where applicable. Moreover maintaining the system health, detection of the failure and recovery to acceptable state are considered as issues to deal with.

Fair and efficient wireless resource sharing must be ensured by medium access protocol since multiple users need to use the same resources. Two major categories of *medium access strategy* are distinguished in WMNs: contention based protocols and collision free channel partition protocols. First type i.e. CSMA [6] assume there is no central entity to allocate channel resources. To transmit each node need to compete for the medium. This is simple but less effective than the second type i.e. TDMA [6] which assign dedicated channel resources to each node wishing to communicate. Since the architecture of WMNs, the ad-hoc network problems like hidden-node or deaf-node are also present [8]. Those contribute highly to application data rate degradation which is explained further.

Since WMNs operate in multihop environment the application data rate decrease can be observed with the increase of the number of hops that transmitted packet needs to be forwarded. Interference range is a distance until which the unwanted received packet can cause collision. Let it is assumed that interference range is five hops and there is only one radio interface. All the nodes in the chain are not able to communicate as depicted on the Figure 2.2. If any of those nodes transmit it will cause the collision at node 2. That causes significant delays. Because of it WMNs are facing a significant limitation of network capacity. It has been found [6] through experiments using IEEE 802.11 MAC protocol that on chain topology, the application data rate degrades approximately to 1/n of the raw channel bandwidth.

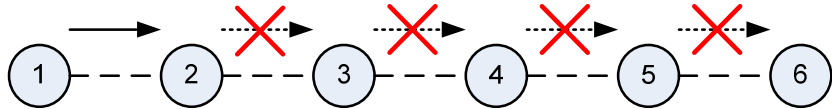


Figure 2.2 - Multihop Chain Topology.

From the Table 2.1 it can easily be seen that application data rate decreases significantly as the path length increases. All of the problems faced in this scenario are because the transmission is on the same channel and there is only one interface. Only the transmission or reception of a signal is possible at the same time.

Table 2.1 – Application Data Rate degradation in a WMN with chain topology (extracted from [6]).

	1 hop	2 hops	3 hops	4 hops	5 hops	>5 hops
Normalized application data rate	1	0.47	0.32	0.23	0.15	0.14
1/ hoplength	1	0.50	0.33	0.25	0.20	0.16

Especially when CSMA/CA-based MAC protocols are employed WMNs show high application data rate unfairness among traffic flows. Gateway node often is a bottleneck due to need of processing aggregated access traffic from client nodes as well as the need to relay and distribute the backhaul traffic [6]. That issue is addressed as Fat Tree traffic flow [6]. As depicted in the Figure 2.3, traffic generated by clients can create high application data rate demand causing bottlenecks close to the

gateway. Clients B get advantage over Clients A, because their signal does not need to be relayed by few more nodes. Moreover as each node injects the same amount of traffic, not only the node needs to transmit the traffic from preceding nodes, but from its own access network as well.

The more neighbours the node has the lower, in terms of hop count, the network can be. Max-min [9] is one of the possible approaches where one maximize the minimal application data rate to ensure that most distant users obtain maximal application data rate available for them.

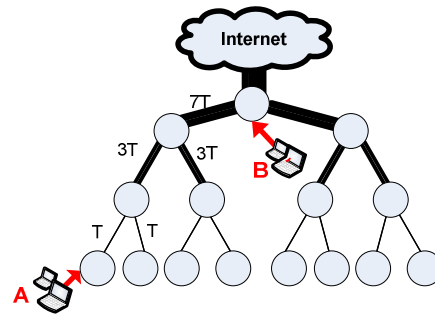


Figure 2.3 - Fat Tree Problem.

In WMNs nodes can form Single-Radio Multi-Channel (SRMC) [6] or Multi-Radio Multi-Channel networks (MRMC) [6] depending on the equipment used. An end-to-end path in multihop network should utilize all the available orthogonal channels in a manner that maximizes the spatial reuse. The key limitation to achieve it in SRMC is the half-duplex mode which prevents nodes from transmitting and receiving at the same time. Even if multiple non-interfering channels are available theoretically it is better to use the same channel in adjacent nodes due to delay caused by scanning, selection and switching of the channels.

In the MRMC networks the nodes can work as a full duplex ones at one time receiving on channel C1 on one interface while simultaneously transmitting on the channel C2 on another interface. For example, let each one hop path (i.e. 1-2) in Figure 2.4 has maximum data rate of R. If one consider path 1-2-3 with the node 2 equipped with one radio and the source (node 1) rate R bps the average received rate at node 3 will be R/2 bps, because node 2 will spend half time receiving and half time transmitting. When two sources will be transmitting at the same time and the paths 1-2-3 and 4-2-5 will be active the average receive rate will be R/4 bps at the endpoints. Having multiple channels does not help, due to only one radio at a node is present. The situation changes significantly when there are 2 radios installed at centre node. Again when the path 1-2-3 is considered the receive rate is increased to R bps. With two paths active 1-2-3 and 4-2-5 the receive rate at end nodes is R/2 bps. In last scenario node 2 will be receiving two transmissions at the same time and then transmitting them simultaneously to the endpoints.

As there is no need to use wired infrastructure, WMN access points can be installed practically everywhere which helps to eliminate zones without signal penetration which is a benefit in *Broadband home networking* [1]. Moreover signal does not need to be processed by router or a hub when client to client connectivity is needed. When the information needs to be shared, it no longer has to go through internet connection thus resulting in cheaper installation of *Community and neighbourhood networking*

[10]. Vast area of coverage is provided with use of WMNs and the robustness to link failures is ensured thus WMN are useful in *Enterprise networking* [11] or *Metropolitan area networks* deployment. With the use of good backhaul internet connections from vehicle, train or ferry and the WMN infrastructure it is easy to provide connectivity to enrich the travelling experience in *Transportation systems* [10]. In *Building automation* any electrical device with ability of remote control can be connected through WMNs with less OPEX costs and more easily than with wired connection. Wherever high portability together with data exchange infrastructure must be ensured WMNs unveil their advantages like in creating *Security surveillance systems* [12] or network based on *WMNs for Earthquakes* [13] scenarios. Time to deploy, ability to relocate and reliability are the key advantages.

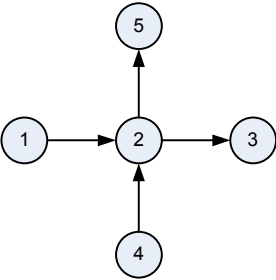


Figure 2.4 - Example topology for SRMC and MRMC comparison.

2.2 Wireless Local Area Networks

As in the wired LANs, WLANs are organised in layered manner where each layer represents logical functionalities of a network protocols that cooperate with each other. This section opens with a description of protocol architecture in WLANs which is followed by various standard amendments that introduce new functionalities.

Most common type of wireless networks nowadays are the networks described in IEEE 802.11 standard [14], where network architecture is hierarchical as illustrated in Figure 2.5. Basic element of each network is Basic Service Set (BSS) which is a group of stations which access to the medium is controlled. An infrastructure-based BSS includes one station that has access to the wired network and is referred to as Access Point (AP). The AP distributes the traffic among stations and every communication between stations is made via AP. An Independent Basic Service Set (IBSS) is the simplest 802.11 network type that is referred to as Ad-Hoc type. It is a network consisting of at least two stations, where no station has priority over other and the responsibility of coordinating the medium access is shared between the stations.

Hidden and deaf node problems [15] are the most common and serious capacity influencing problems in wireless networks. A *hidden node* is defined in the context of a given transmitter–receiver pair. A node is said to be hidden from the transmitter if it can cause a collision at the receiver by transmitting, but cannot perceive any signal sent by the transmitter. For instance, nodes C and F are hidden nodes, for the transmitter–receiver pair, A and B, in Figure 2.6. While node A is transmitting to node B, if either node C or node F begins transmitting, there will be a collision at node B. The problem can be

mitigated by requiring nodes A and B, to execute a handshake (e.g., RTS-CTS in IEEE 802.11), to reserve the channel, before every data transmission. However, the success of this handshake mechanism is severely hampered. As presented on figure Figure 2.5 node F is further than node C from node B. Assuming that node C is still in transmission range of node B and node F is not the node F may cause a collision. If there would be transmission from A to B, node C will receive CTS message and will hold the transmissions, while node F will not receive it and can start transmitting at any time causing collision.

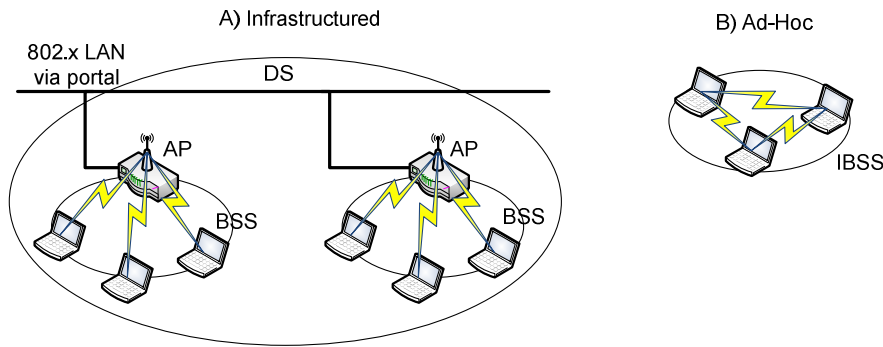


Figure 2.5 - Architectures of IEEE 802 Networks (extracted from [14]).

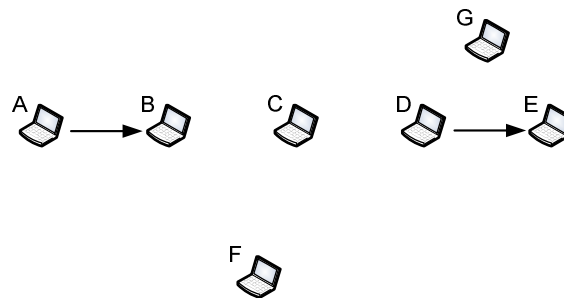


Figure 2.6 - Illustrating the hidden and deaf terminal problems (extracted from [15]).

A *deaf node* is the one that is unable to interpret the handshake messages from a transmitter–receiver pair in its neighbourhood. In Figure 2.6, node C will not be able to interpret the CTS from node B to node A, if there is an on-going data transmission from node D to node E. This is because many packets are already received by C, although they are intended to E, so that they are regarded as noise. Because of this if at this point the node B sends the CTS message, node C will not receive it as it will be simply a collision with the packet received from D. Thus, the purpose of the CTS from node B is defeated. Once the transmission from node D to node E is completed, node C could send out an RTS and cause a collision at node B, since node C did not set the NAV vector when the CTS from B has been transmitted.

For single radio nodes the Request To Send- Clear To Send (RTS-CTS) [14] handshaking mechanism is introduced. When using multi-radio nodes utilizing several channels mechanism mentioned before is not enough to avoid collisions. The nodes receiving on one channel are not aware of currently ongoing transmissions on the other. This is why, to avoid collisions after switching the interface to other channel the backoff [14] period is used. It is amount of time that node needs to send a full maximum sized data frame together with all overheads used. During this period node listens to the channel and

afterwards it knows whether the channel is ready for transmission or not.

All of the abovementioned schemes add themselves to the total delay of the packet received at the node. An example is shown in Figure 2.7 for IEEE 802.11 CSMA/CA based, where IP/TCP/MAC/PHY headers, MAC contention, acknowledgement (ACK) are illustrated not in proportion to the data packet. This is a very limitation factor, especially when the network is dense and many nodes compete for the same channel of transmission medium.

The 802.11 in its origins defines a few supplement standards, four of which are presented as possible to implement in WMN architecture. Main features are seen in Annex B. Application data rate decrease in each type is derived from overhead of CSMA/CA media access method, while the range shortening in 802.11a is due to higher frequency band than in other two standards. Orthogonal Frequency Division Multiplexing (OFDM [14]) transmission scheme enables to achieve higher Bit Rate in 802.11a and 802.11g than in 802.11b.

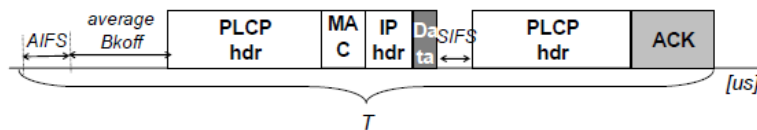


Figure 2.7 - IEEE 802.11 overhead of a data packet (extracted from [16]).

One of the state of the art amendments to IEEE 802.11 standards is 802.11n [17]. It enables wireless nodes to use Multiple Input Multiple Output (MIMO) technology which uses multiple antennas for simultaneous transmit and reception of signal (usually 2x2). Moreover equipment using 802.11n technology can bring together a few transmission canals to form one link which quadruples the application data rate available. The physical channels are twice wider than in for example 802.11g increasing the physical data rate possible to transmit over single channel. Since 4 links are possible to use at the same time the MRMC WMN networks can be easily built on that technology.

As each of 802.11a/b/g/n standards are defined to work in one-hop infrastructure based topologies the 802.11s [10] amendment was developed to make WLANs useful in creating WMNs. It uses 802.11e channel access method as the base of medium access mechanism. Network architecture can be divided in the two main areas: BSS and ESS. Mesh Links (MLs) wirelessly interconnect the Mesh Access Points (MAPs) that represent different BSS. Stations (STAs) connect to MAPs with different frequency than MAP in ESS to avoid conflicts between two types of networks. Mesh Points (MPs) that do not have Access Points capabilities can provide relaying services or act as a Portal to other broadcast domains as can be seen on the Figure 2.8. With the usage of 802.11s mechanisms it is possible to make a medium reservation both in frequency domain as well as time domain. It is possible to handle QoS in a multihop environment. Since neighbouring MPs mutually inform each other about their own, their neighbours' and the neighbours' of their neighbours intended transmissions, mutual interference can be prevented and frame transmissions have higher success probability, thus enhancing overall spectrum usage. As MPs arrange their frame transmissions, arbitration periods that are a waste of capacity can be prevented. What is more segregation of BSS and mesh traffic, to prioritizing mesh backhaul over local BSS frames and to making use of one or

more frequency channels with one or more transceivers is possible as well.

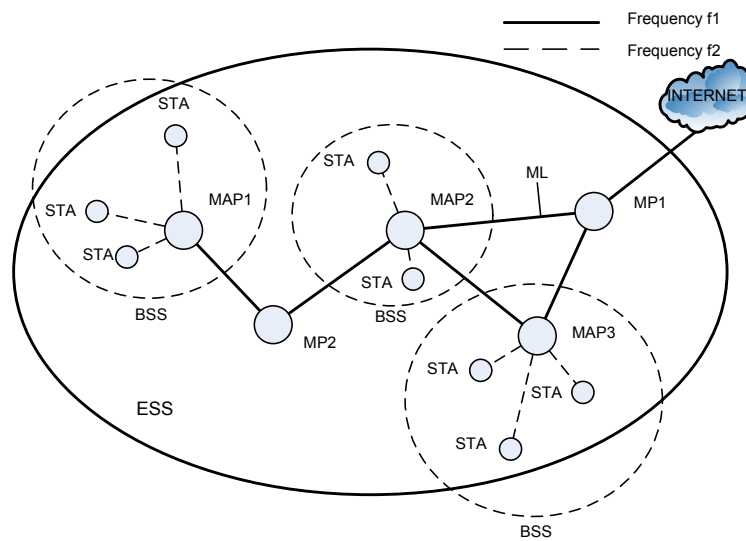


Figure 2.8 - Network Architecture of 802.11s.

2.3 Wireless Mesh Networks deployed over Wireless Local Area Networks

Usually in Wireless Mesh networks nodes are equipped with N_{int} interfaces, using N_{ch_ort} orthogonal channels, where $N_{int} < N_{ch_ort}$. Let it be assumed that one interface uses one channel at a time. There are protocols proposed which make possible to utilize large number of channels with few interfaces available. Good transmission scheduling must be used however, because one node can receive from only one other node at the time. Few approaches of addressing channel assignment are considered and some of them are reviewed further in this section.

One possible approach [18] to utilize large number of channels with single-radio nodes is to use MMAC link layer protocol which is a distributed way of assigning channels. All nodes periodically meet on a common channel where they publish the channels they will be on until next meeting period. When the connection is to be set communicating nodes exchange the preferable channel list (PCL) where the most preferable channels to use in the nodes neighbourhood is stated. Those are the least occupied channels in their vicinity. From two lists one most preferable channel is chosen and the nodes tune into that channel to continue transmission until next rendezvous period. Other nodes update their PCL list by overhearing the initialization period on the common channel where nodes exchange coordination packets agreeing which channel to use. That ensures efficient distribution of traffic across channels what was shown in [18] where comparison simulation between MMAC and 802.11 DCF and DCA was conducted, proving that MMAC outperforms remaining two.

When a node with multiple interfaces is considered the proposed approach Hybrid Multi-Channel Protocol (HMCP) [18] is to fix one interface on a channel and announce that to neighbouring nodes while the other channel is left to be switchable one. Different fixed channels need to be used in vicinity

to decrease interferences. Sender node being aware of fixed channels of adjacent receiver nodes tunes in his switchable channel to the one that the receiver is communicating with. To maintain effective usage of fixed channels nodes are monitoring the table where number of nodes using each channel is stated. When the distribution is not equal, node changes its fixed channel to the one that is the least used. Since the nodes may be listening each on different channel, broadcast message needs to be sent on each channel separately thus increasing broadcast message overhead in comparison with a MMAC. HMCP was proven to be much more effective than single channel protocol [18]. Increase of application data rate was observed in the function of the number of available channels, reaching quadrupled application data rate compared to single channel protocol while using HCMP with 12 channels. HMCP offers higher application data rate and avoids bottlenecks by using different channels on successive hops, and by using the two interfaces to receive and send data in parallel.

Another mechanism of channel assignment is Load Aware Channel Assignment [19] (LACA) algorithm which bind each network interface to a radio channel in such a way that the available bandwidth on each virtual link (pair of nodes) is proportional to its expected load. Interferences table is composed and shared between nodes. LACA algorithm requires four inputs: estimated traffic load for all communicating node pairs, wireless mesh network topology, number of 802.11 NIC on each node and number of non-overlapping channels on each node. Table of seed links is visited in decreased order of criticality or expected load of a link. On that virtual link the channels are being reassigned in three possible scenarios: new channel is assigned to both nodes when those have free slot in their lists, node with free slot takes over the channel from the node that has the list full or when both nodes have their channel lists full one channel from their lists is taken and assigned to both, in the way to decrease the interferences in the interference tables. This algorithm avoids bottlenecks and is proven good in load balancing and increasing cross section goodput, which without overheads and signalling is the real application data rate available. Studies [19] showed that in 100 nodes grid topology with 20 of ingress/egress nodes, LACA experiences increase in goodput along with increase of available channels to use from as well as with increase of NIC per node. When the tests with various numbers of ingress/egress nodes were conducted the LACA was almost 10 times better than single channel algorithms [19].

More ideas for channel assignment are described in [20]. In the network architecture called Hyacinth nodes have at least 2 NICs and are prioritized by the hop count from the gateway. Nodes choose the channels in the decreased order of priority that grants the gateways to choose as the first ones. At first the interface-neighbour binding is made. NIC are divided in 2 groups: UP-NICs that are used to communicate with nodes closer to the gateway (parents) and DOWN-NICs to communicate with the rest nodes (children). Interface channel assignment is made periodically to balance the load. Each node chooses the least interfering channels in area to communicate with the children, that means channels for UP-NICs are chosen by parents of the particular node based on the total load information. Refraining from choosing the channels used by parents results in fat-tree architecture. One NIC can be used to communicate with several nodes. Parent-children distinction avoids ripple effects in the network where change of one channel binding causes changes propagating down the whole network. Results from simulations [20] show that in 60 nodes grid topology network the average

goodput, while using only 2 NIC is 6 to 7 times improved in comparison with single channel network of the same topology.

Similar method, but centralized one is Mesh based Traffic and Interfere aware Channel assignment scheme (MesTIC) that is proposed in [21]. MesTIC gives rank to each node based on: number of radios, aggregate traffic and minimum hops from gateway. Rank determines the priority of assigning the channels for link emanating from node. The topological connectivity is ensured by a common channel on separate radio that is chosen as first in the assignment process. The algorithm visits nodes only once and distributes the channels to the links that carry the highest traffic first. Being originally developed for one gateway architecture MesTIC needs some changes to work in multi-gateway environment. This scheme outperforms other traffic aware centralized channel assignment schemes based on Hyacinth architecture in terms of aggregate application data rate. The tests were made on 5x5 grid topology, with 3 radios- one for communication and 2 effective ones on each node.

In the IEEE 802.11s standard the Common Control Channel (CCC) protocol is described and the performance of it is measured in [22]. CCC is a distributed, contention-based dynamic channel assignment scheme. On the common Control Channel (CC) that is served by separate radio the transmission opportunities (TXOP) are scheduled possible to acquire by any node. The first node that advertised transmission is granted the right than in the handshake process still conducted on CC node reserves particular channel to be used on Mesh Traffic channel (MT) to communicate with receiver node for the period of TXOP. With two radios at each node operating in the 802.11a band there was one that was a control radio and one traffic radio. The tests were run with 4 to 8 traffic flows simultaneously and it was showed that the maximum capacity is reached when the number of MT channels available is the same as number of flows. Important reported fact was that even though control channel was operating at only 6Mbps it was not a bottleneck even when the total traffic on MT was 280Mbps.

Chapter Three

Algorithm and Simulator Description

This chapter presents the parameters used for results analysis, network model and node model used in the work. Later the Radio Channel Allocation algorithm is presented. Finally the OPNET Modeler Wireless Suite is described, which is the software used for simulations done in this work.

3.1 Performance Analysis

Following is the description of the parameters that are used to measure and analyse the performance of the implemented algorithms for radio resource management as well as ones depicting the state of the signal or network itself. Each parameter is briefly described with mathematical as well as logical explanation provided.

The following parameters are to be used for evaluating the performance of the network in analysed scenarios. The delays and the Packet Error Ratio are to be kept below certain value in order to assure stability in network.

Transmission range $d_{tx[m]}$ is a radius around the node that the nodes can successfully receive and decode the packets from a transmitting node.

Theoretical Interference range, $d_{i.t[m]}$, is a distance measured in meters or in the number of hops from a particular node that shows significant interference presence. This range depicts the area in which channel reuse strategy should be kept tightly in mind in order to increase transmission data rates.

Opnet Interference Range $d_{i.o[m]}$ is an interference range measured in OPNET, and chosen under the maximum allowed PER and maximum delay conditions. It shall be shorter than theoretical interference range as some packet loss is tolerated.

Data Rate, $R_{[Mbps]}$, is a total number of bits received by interface per second. It contains all the communication protocol overhead.

Maximum Voice Packet Delay $\tau_{max[ms]}$ is a maximum delay that the voice packet should experience in order to stay usable for efficient communication.

τ_{static} is a period of time between attempts to change the channel that static interface transmits on.

$\tau_{dynamic}$ is a period of time between attempts to change the channel that dynamic interface transmits on.

End-to-end delay, τ_{e2e} [19], is a time taken by the packet to be transmitted across the network from source to destination. It describes either the length of route that packet has passed or the congestion of the network. This parameter is to determine whether the VoIP call can be supported in a network.

$$\tau_{e2e[ms]} = \tau_{rx[ms]} - \tau_{tx[ms]} \quad (3.1)$$

where:

- τ_{rx} is a time when a packet arrives to the destination,
- τ_{tx} is a time when a packet is sent from the source.

Number of one hop neighbours, N_{ohn} , is a number of nodes that are in the transmission range of a particular node.

Node ring N_r is number of hops to the gateway that characterises a set of nodes with the same distance in terms of hop count from the gateway.

Average end-to-end delay, τ_{e2e}^{av} is the overall delay observed on a link.

$$\tau_{e2e[ms]}^{av} = \left(\sum_{i=1}^{N_{p_ar}} \tau_{e2e[ms]}(i) \right) / N_{p_ar} \quad (3.2)$$

where:

- $\tau_{e2e}(i)$ is end-to-end delay of a packet i
- N_{p_ar} , is the number of packets that arrived.

r_{SINR} [19] is a signal-to-interference-plus-noise ratio, which describes the quality of signal by comparing the level of desired with undesired signals. The higher SINR is the better signal is received thus higher data rate can be obtained.

$$r_{SINR[db]} = 10 \log_{10} \left(\frac{P_{S[W]}}{P_{N[W]} + P_{I[W]}} \right) \quad (3.3)$$

where:

- P_S , is power level of the signal,
- P_N , is the noise power level,
- P_I , is the interference power level.

Offered application data rate, $R_{app_offered}$ is the volume of traffic without overhead injected into the network:

$$R_{app_offered[bps]} = S_p[b] / (r_{p_int[1/s]}) \quad (3.4)$$

where:

- S_p is a size of the packet,
- r_{p_int} is the packet interarrival time.

Application data rate R_{app} is a number of bits received per second by an application layer of a node.

Application data rate generation ratio, r_{app_gen} is showing the diversity in traffic characteristics. The higher it is the more uplink traffic is being generated.

$$r_{app_gen} = R_{app_rec_i[kbps]} / R_{app_gen_i[kbps]} \quad (3.5)$$

where:

- $R_{app_rec_i}$ is traffic received at node i ,
- $R_{app_offered_i}$ is traffic offered at a node i .

The RTS-CTS effectiveness [23], $r_{RTS/CTS}$, parameter has been adopted to this study. It is a ratio of a size of the transmission range to the size of the theoretical interference range. It describes the ratio

between the areas inside which the RTS-CTS messages are received successfully to the area where the RTS-CTS messages are causing collisions due to the fact that their SINR is not sufficient to be decoded.

$$r_{RTS/CTS} = \begin{cases} 1 & \text{for } 0 \leq d_{n2n} \leq 1/\varepsilon \times d_{tx} \\ 1 - [\pi - \cos^{-1}(\frac{d_{n2n}}{2 \times d_{tx}})] \times \frac{\varepsilon^2 \times d_{n2n}^2 - d_{tx}^2}{\varepsilon^2 \times \pi \times d_{n2n}^2} & \text{for } 1/\varepsilon \times d_{tx} \leq d_{n2n} \leq d_{tx} \end{cases} \quad (3.6)$$

where:

- d_{n2n} is a node to node distance
- ε is interference coefficient
- d_{tx} is transmission range

Channel reuse distance, d_{ch_re} is a distance in number of hops between two nodes using the same channel.

Active nodes, N_{n_act} number is the number of nodes simultaneously transmitting to and receiving traffic to and from gateway.

Hello Update time, T_{hello} is the time between the broadcast of hello packet and the exert of this fact by other node. This usually is CUT update.

Convergence time of the network, τ_{conv} is a period of time when all of the channels are assigned to each nodes static interface.

3.2 Network and Node Model

The main problem that is going to be discussed is overall performance optimisation of Radio Allocation Algorithm developed in [4] in terms of fairness, delay and reception assurance. The goal is to assure the user experience on the highest level possible of fairness and good quality of connection. For doing so the network model is defined. The network overall architecture has already been depicted on Figure 2.8 and it has got features and assumptions listed below:

- Each node is a connection point between backbone and access network,
- Backbone network is used for connecting the nodes with each other to forward traffic to the gateway,
- Each node`s access network is simulated by generating packets and in this way simulation of traffic generated by users is made,
- Wireless systems used in backbone and access networks use non overlapping frequencies,
- There is one gateway to which all the traffic is heading to that is connected with a cable pipe or fibre optic,
- Line of sight (LOS) between the nodes is maintained as the rural scenario with free space model is simulated,
- The channel conditions are time-stable and known,

- Transmitted power, antenna gain, path loss and data rate of the interfaces are known and do not vary in time, as it is limitation of OPNET software,

Besides those assumptions two groups of parameters have been defined. One group is defining the topology characteristics that identify the size and density of the network to study:

- The nodes are distributed in the average distance $d_{n_{av}}$ among them,
- Number of one hop neighbours of a node is N_{ohm} ,
- Average number of hops to the gateway is $N_{h_{av_gw}}$,
- Total number of nodes in the network is N_n ,

The second group of parameters is the one that define the wireless characteristics of interfaces. Those influence the maxmin application data rate, $R_{app_{maxmin}}$ that will be available to achieve by the network:

- The data rate of each wireless interface at every node in the network is R ,
- Number of available orthogonal channels is $N_{ch_{ort}}$,
- Transmission power of backbone interfaces is the same at each node P_{tx} ,
- The traffic rate generated at the nodes is $R_{app_{offered}}$

Node model developed for the studies is presented on Figure 3.1. Each node has got two interfaces:

- Static-radio used mainly for receiving packets from other nodes,
- Dynamic-radio used mainly for transmitting packets to other nodes,

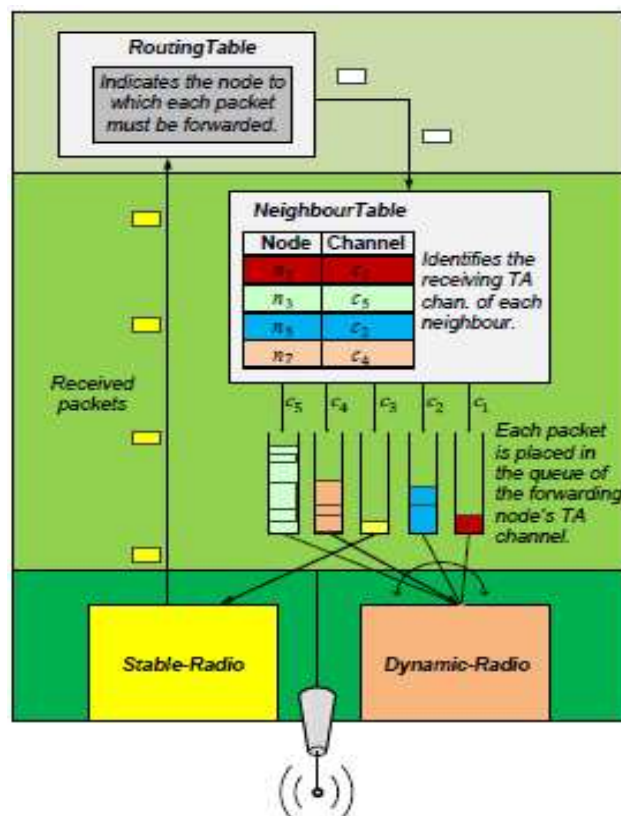


Figure 3.1 - Node Model (extracted from [4]).

Each node maintains the Neighbour Table (NT), with node columns that contain information on IP, MAC and a channel of static interface of other nodes that are one hop away. Packets arriving from IP layer, in the figure represented by Routing Table, contain information to which node (IP address) they need to be transmitted to. According to neighbour table packet is inserted into proper output queue, which is served by Link Layer and awaits there to be transmitted. The RCA works between 2nd and 3rd ISO/OSI layer and is invisible for them.

Static radio is fixed on one queue and one channel for a relatively long period of time, allowing other nodes to transmit to it. Dynamic radio is serving the remaining queues in round-robin scheme, thus transmitting on channels that are left. The allocation of channel to the static and dynamic radios and maintaining of a neighbour table is regulated by a Radio Channel Allocation (RCA) algorithm.

By collecting and analysing the packets arriving to the node each node maintains statistics about the traffic served, and its position in the network. Each node is defined by parameters:

- End-to-end delay τ_{e2e} ,
- Signal to Interference plus Noise Ratio r_{SINR} ,
- Number of hops to the gateway N_{h_gw} .

The theoretical value of application data rate that each node can inject into a link and assure maxmin fairness is R_{app_maxmin} , later on this value will be address only as R_{app} . The network is maxmin fair when there is no possibility of increasing the value of application data rate so that none of the nodes is experiencing the decrease in service rate. The limitation here is the radio interface rate of gateway node as whole traffic is accumulated and must be transmitted at this point as presented on Figure 3.2, where each node must be assured to receive the G application data rate. The gateway node also generates access traffic but it is not significant as the access radio interface is operating at orthogonal channel to the backbone one and the access traffic is injected directly into cable connection with the internet.

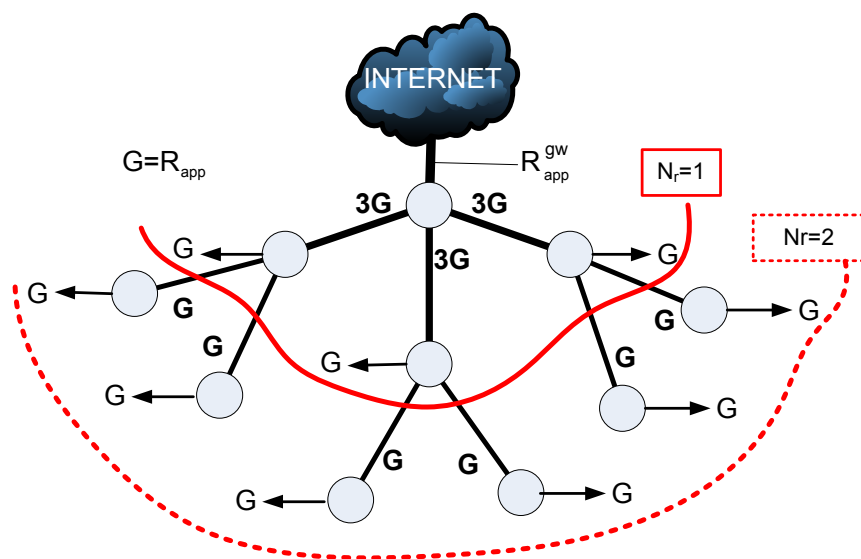


Figure 3.2 - MaxMin Application Data Rate calculation for $N_{ohn} = 3$ topology.

On Figure 3.2, the proposed way of calculating the R_{app} is presented. All of the nodes must receive the same application data rate to achieve MaxMin Fairness. Since the model of node is having one interface for receiving and one for transmitting the R_{app} is highly dependent on the time that dynamic interface can transmit to the neighbouring nodes.

The way of calculating is using simple division of time that gateway interface can spend on transmitting or receiving the traffic destined to particular node. It is rough estimation. This is independent from position of a node in the network as following assumptions are made:

- There are no interferences between transmissions and there are no collisions as the channel allocation is ideal,
- Nodes can transmit and receive simultaneously (2 radio interfaces) so the wireless route between the source (gateway) and destination (any node) behave as a wired link with cumulative delay consisting of all the channel access and queuing delays at the intermediate nodes,
- There are no hidden nor deaf node problem,
- Traffic is heading only in one direction i.e. only downlink or only uplink.

As the cases of bidirectional traffic are going to be studied as well the method of calculating theoretical maximum for bidirectional traffic is presented as well. As the traffic sent from the gateway is being forwarded through dynamic interface, and the one received by gateway is received on static interface their capacity can be separated. That is why in (3.1) for bidirectional traffic the method of calculating the theoretical maximum is by multiplication of 2- the number of interfaces present at a node.

Theoretical value of maxmin application data rate, R_{t_app} is :

$$R_{t_app}[\text{Mbps}] = \begin{cases} R_{app}^{gw}/N_{n_rec} & \text{for unidirectional traffic} \\ 2 \times R_{app}^{gw}/N_{n_rec} & \text{for bidirectional traffic} \end{cases} \quad (3.7)$$

Where:

- N_{n_rec} number of simultaneously receiving nodes.

3.3 Propagation Model

The communication between wireless nodes can be achieved only when the power level of signal received, P_{rx} , at a node is above set receiver sensitivity, P_{min} . This depends on three groups of parameters:

- Wireless system and the frequency band used in it,
- Distance between communicating nodes,
- Attenuation, interference conditions of the channel and sensitivity in receiver node.

Signal level received at the node is depends on transmitted power level and both receiving and transmitting antenna gains, which are focusing the radiated power in the particular direction thus

resulting in stronger signal. The signal power is being decreased by the losses of the environment that transmission is in. The power received at node M_r from M_t , $P_r(M_r \leftarrow M_t)$ is [24]:

$$P_{rx}(M_r \leftarrow M_t)_{[mW]} = \frac{P_{tx}(M_t \rightarrow M_r)_{[mW]} \times G_t(M_t \rightarrow M_r) \times G_r(M_r \leftarrow M_t)}{L_p(M_t \leftrightarrow M_r)} \quad (3.8)$$

where:

- M_r is a receiving node,
- M_t is a transmitting node,
- $P_t(M_t \rightarrow M_r)$ is the transmitted power from M_t to M_r ,
- $G_t(M_t \rightarrow M_r)$ is the gain of M_t transmitting antenna in the direction of M_r ,
- $G_r(M_r \leftarrow M_t)$ is the gain of M_r receiving antenna in the direction of M_t ,
- $L_p(M_t \leftrightarrow M_r)$ is a path loss between M_t and M_r .

Propagation model that is used in simulations is standard free-space model as the simulations are assumed to have clear LOS [24]. The higher the frequency of transmission is and the greater the distance between communicating nodes the higher level of attenuation is present. Path loss is given by L_{p0} :

$$L_{p0[dB]} = 20 \log(d_{[km]}) + 20 \log(f_{[MHz]}) + 32.44 \quad (3.9)$$

where:

- d is the distance between transmitter and receiver,
- f is the frequency of the signal.

The above model is possible to use only for initial estimates. The propagation model implemented in the simulator used in work is [24]:

$$L_{[dB]} = L_{p0}(d_0[km]) + 10 \times a_{pd} \times \log(d_{[km]}/d_0[km]) + \Delta L_{[dB]} \quad (3.10)$$

where:

- d_0 is a reference distance: for practical systems operating at 1 to 5 GHz it is 100m for outdoor environments,
- a_{pd} is average power decay, where $a_{pd} = 2$ is a value for free space. It is higher when obstacles are present.
- ΔL is a log-normal shadowing, a zero-mean Gaussian distributed random variable with standard deviation $\sigma\Delta L$.

Above parameters depend on the structure of the environment that the signal is propagating in. When the density of material used for buildings is higher the signal has got more troubles to pass it through. For urban environments consisting of concrete and steel high rise buildings, the $a_{pd} = 3.3$ and $\Delta L = 5.9$ dB, while for small wooden houses and dense foliage $a_{pd} = 4$ and $\Delta L = 8$ dB is taken [24].

Interference is the main factor limiting the capacity of wireless networks. The model used in the work

is physical interference model, which is the most accurate among others [4]. The more nodes are communicating in the interference range and using the same frequency the higher the interferences become.

The interference function is given by:

$$SINR(M_r \leftarrow M_t) = \frac{P_r(M_r \leftarrow M_t)}{P_{N_0} + \sum_{M_i \in J} P_r(M_r \leftarrow M_i)} \geq P_{SINR}(R) \quad (3.11)$$

Where:

- $P_{SINR}(R)$ is the SINR threshold for a certain MCS, Table B.2, directly related with a certain data-rate (R). In fact, in communications, errors cannot be completely eliminated; hence, success is in the sense of achieving a Bit-Error-Rate (BER). For successful decoding, a minimum BER is specified for each MCS, which can be translated into a minimum SINR threshold,
- P_{N_0} is the Average White Gaussian Noise.

Considering a transmission from M_t to M_r , interference increases as more neighbour nodes transmit simultaneously on the same channel in the same neighbourhood. Increase of interferences decrease the SINR power which needs to stay above $P_{SINR}(R)$ to assure reception.

The model used in the thesis is defined to have two ranges: the transmission d_{tx} and the theoretical interference range d_{i-t} . Transmission range is defined as a certain surface covered by a radius of d_{tx} around the transmitter node, where reception is possible. The theoretical interference range is defined as the radius, outside which the transmitter will not interfere with other transmissions. A node in the WMN can have multiple neighbours within transmission range, but not all of them act as a next hop in the route path. If neighbours within the transmission range are not a direct next hop, they are recognised as interfering nodes. This means that each transmission made by node situated further than last One-Hop neighbour and before the theoretical interference range shall result in increasing the noise received by a node using the same channel as transmitting one.

Using equations (3.4) and (3.5) the equation for theoretical interference distance is calculated, based on [15]. The calculation assumes that there is no noise in the background from any other interferer and there is only one node interfering with the considered node. The calculations are presented in Annex C.

$$d_{i-t} \geq d_{n2n} \times 10^{\frac{P_{SINR}}{10 \times \alpha_{pd}}} \quad (3.12)$$

where:

- d_{i-t} is the theoretical maximum interference range,
- d_{n2n} is a node to node distance.

3.4 Radio Channel Allocation algorithm

The RCA algorithm was derived from [4]. It focuses on minimising interferences and maximising the available application data rate and connectivity. It is an algorithm proposed for spontaneous and opportunistic usage of radio resources. It connects a few functionalities of other channel assignment allocation strategies presented before in the chapter 2. Those are:

- Utilizing static and dynamic radio interfaces, like in HMCP [18],
- Creating, sending and processing Hello packets which contain info about static channel used by a particular node M and interference neighbourhood of node M, like in MMAC [18],
- Evaluates the channel utilization in interference neighbourhood, depending on the scheme chosen. It uses either only the channel usage number, as in LACA [19] algorithm or evaluates also the distance of the node to the gateway as in HYACINTH [20].

The main functionalities are listed [4]:

- Neighbour Table (NT): is being maintained by each node, NT contains static channels, IP and MAC address of one-hop neighbours,
- Channel Usage Table (CUT): contains information about utilization of channels inside interference neighbourhood. It is used for making a decision for periodic static channel change,
- Packet queue per channel: each node keep separate queue for each channel that the interfaces can transmit on,
- Dynamic radio channel switching: the dynamic radio is switched in the round-robin way. The channel change happens only in 2 circumstances: when the queue that dynamic radio is serving is empty and there are packets in other queue or when the dynamic radio was fixed on the channel for more than $\tau_{dynamic}$,
- Hello messages broadcast: periodically, each T_{Hello} seconds the node broadcasts the Hello packet containing: IP and MAC address of static interface as well as frequency that it is currently transmitting on. Together with it the CUT is being spread out,
- Updating NT and CUT: when a node receives the Hello packet it updates any information in NT and CUT. Usually the most important ones are the frequencies of static channels,
- Static-channel selection: When the node connects to the network it selects the static channel to use and afterwards periodically each T_{Hello} as well. According to algorithm the least used channel from interference neighbourhood is taken and assigned. Just after that Hello message is broadcasted,
- Gateway announcement: The gateway announces itself through a broadcast message. It is being forwarded by each node and the field with hop count number to the gateway is being incremented,
- Average received power: each node calculates, for each static channel the average received signal power from its neighbouring nodes.

- When the node is about to start the change of static channel frequency it looks up the channel utilization table, counts the channel usage and chooses the channel minimising the usage of all the channels. Immediately after that Hello packet is broadcasted.

Depending on the wireless system used there are always several channels to choose from. Channels that interfaces can use are $C: \{C_1, \dots, C_{N_{ch_ort}}\}$, where N_{ch_ort} is a positive, integer number of non-overlapping channels that a particular system of use can offer.

The RCA chooses the new static channel every hello packet interval T_{Hello} in few simple steps:

1. Activity A is calculated:

$$A(M_a, C_c) = \begin{cases} 1 & \text{if } M_a \text{ has got } C_c \text{ assigned in the neighbour table} \\ 0 & \text{otherwise} \end{cases} \quad (3.13)$$

where:

- M_a is a mesh node a ,
- C_c is a channel c ,

2. Usage U_T , of each channel used by all the nodes in the interference neighbourhood is computed.

There are two Utilization Function (UF) possible to use for evaluating the channel usage.

2.1. First one is Less Used Channel Utilization Function (LU), which simply counts the number of nodes using each channel:

$$U_{T_LU}(X_m^{C_c}) = \sum_{M_a \in X_m^{C_c}} A(M_a, C_c) \quad (3.14)$$

where:

- $X_m^{C_c}$ is a interference neighbourhood of a node m in which the c channel is being used

2.2. Second UF possible to use for evaluating channel utilization is Weighted Less Used (WLU) UF. It counts, just like LU, the number of nodes using the particular channel on static interface. Difference is that each value before inserting into UT is multiplied by the weight of a node. The weight function $W(N_{h_gw}(M_a))$ is presented in (3.9) and the values are $W: [0,1]$. Weights are assigned depending on the nodes` distance to the gateway N_{h_gw} . The lower the N_{h_gw} , the higher the weight. By doing so a prioritization of channels takes place. Channels used by nodes closer to the gateway are more important because they need to carry more traffic. This implies that the channel is being active for longer period of time increasing the chance of collision when the same channel is reused. The gateway node is the most important one, and its weight is the highest to assure that the channel used by it is not reused.

$$W(N_{h_gw}(M_a)) = \begin{cases} 1, & \text{for } N_{h_gw} = 0 \\ 1/(N_{oh_n} \times 2^{(N_{h_gw}-1)}) & \text{for } N_{h_gw} > 0 \end{cases} \quad (3.15)$$

$$U_{T_WLU}(X_m^{C_c}) = \sum_{M_a \in X_m^{C_c}} (A(M_a, C_c) \times W(N_{ngw}(M_a))) \quad (3.16)$$

3. With above data node is provided with the knowledge about utilization of all the channels and the best channel to use in static interface is the one with lowest usage:

$$C = \{C_k, k \in \{1, \dots, N_{ch_ort}\} : \min U_T(X_m^{C_c})\} \quad (3.17)$$

By all of presented above functionalities there are a few parameters of RCA which influence the output of it the most. Those are:

- Period of time between static interface change attempts τ_{stable} , also *Hello* packet interval T_{Hello} ,
- Period of time between dynamic interface change attempts $\tau_{dynamic}$
- $K_Neighbourhood$ parameter, which defines the distance in number of hops that inside which the node evaluates the usage of radio channels.

More parameters influence the RCA output. Those however are connected with:

- Wireless system used - number of orthogonal channels to choose from N_{ch} ,
- Network topology - distribution of the nodes which directly defines N_{ohn} ,
- Traffic characteristics - activity of the nodes, with the traffic intensity and characteristics

Radio Channel Allocation algorithm depending on this value evaluates the channels utilization until $K_Neighbourhood$ hops away. Changing the value of $K_Neighbourhood$ will change the area taken into consideration when evaluating the interferences level during new static channel assignment.

As the $K_Neighbourhood$ is becoming larger, the more extensive the influence of static channel change is. The algorithm process as follows. When the new channel is assigned to static interface the Hello packet is broadcasted. When the hello packets are being received the CUT is being updated by the nodes that received the packet. The most influenced by the channel change are one-hop neighbours so it is probable that they may change the static interface` channel as well. This iteration continues until the $K_Neighbourhood$ distance.

It is possible that maximum time between the channel change by one node and the influence of it exerted on the other node, takes up to $k_neighbourhood \times T_{Hello}$. This fact may create echo of static channel change that ripple for longer time.

3.5 OPNET Modeller Description

OPNET Modeller [3] is a complex software designed to perform comprehensive simulations that concern communication networks. OPNET Modeller accompanied by OPNET Wireless Suite is a perfect tool to analyze Wireless Mesh Networks. The description of a software, its functionalities, and capabilities is provided in this section.

Modeller represents networks in hierarchical structure of three main domains with editor associated to it: network domain, node domain and process domain, presented on Figure 3.3. The main editor, network domain, is the project editor which is the central place of graphical user interface and it is here that the topology of a network is being defined. One can choose from wide range of predefined objects or create them from scratch. When large networks come into consideration it is possible to break their complexity by modelling abstraction layers known as subnetworks. Theoretically there is no limitation to a complexity of the network, practically however the computational time used for running simulations is limiting the size of networks.

Node models can be edited in the node domain. Nodes can be workstations, mobile devices, PDAs, routers, gateways, base stations or any other communication network type equipment. Node models are developed in node editor and consist of functional entities called modules that are connected among themselves. Each module represents specific functionalities and parts of the node. Packets flow between the modules being processed by them. The modules that are defined are: processors, queues generators, receivers, transmitters or antennas. Modules like transmitters and receivers responsible for connection with communication links have predefined functions that cannot be changed, while others like queues or processors are highly programmable giving the user high flexibility in defining processes which are the scope of lower process domain. Transmitters are being considered as data sinks of the node, because all the packets are sent out through them. Receiver on contrary are recognized as interface between communications links and the internal packet streams so it can be said that receivers are data sources, because all the packets arrive via them. Processor modules are processing data packets transmitted through the node. The queue models are divided into subqueues to facilitate buffering and managing the collection of data packets.

Nodes are connected with communication links that allow the communication between the nodes in the form of packets. Connections are created between transmitters and receivers. The copper, fibre optic as well as radio connections can be established. A radio links that are used in WMN simulations are dynamically established during simulation. Since radio is a broadcast technology, the transceiver pipeline must evaluate the connection possibility every time connection is going to be set. The characteristics and even the availability of these links can be subject to time-varying factors such as the movement of communication sites, modification of transmitter and receiver attributes, and interference from other concurrent transmissions. With the optional Terrain Modeling module, terrain and atmospheric effects can be modeled to affect the performance of radio links.

Processes are mainly event triggered and are represented by State Diagram Transitions (STDs). STDs consist of states and transitions where states are representation of process` modes, while transitions specify the changes of the state that can occur for the process. State generally consist of state variables and state executives, where variables are private variables inside the process used for processing actions and executives are actions performed by the process when it is entered or exited. The executives of a state are split into enter and exit executives which allow execution of separate function depending on the transition.

There are two possibilities of a state to be in. In unforced state there is a Blocked state waiting for

interruption between executions of enter and exit executives. The forced state does not let the process to wait and completes the execution of executives one after another. Transitions describe the change of a process from state to state. Transition consists of: source state, destination state, condition expression and an executive expression. Transitions can be heading from one state to another or can be a return transition which origin is in the same state that the destination is. Condition expression defines the requirements for a transition while the executive expression defines the actions to be taken while executing a transition. The Proto-C programming language is used to create a process model. It is a combination of a diagrams and a C/C++ features of programming language.

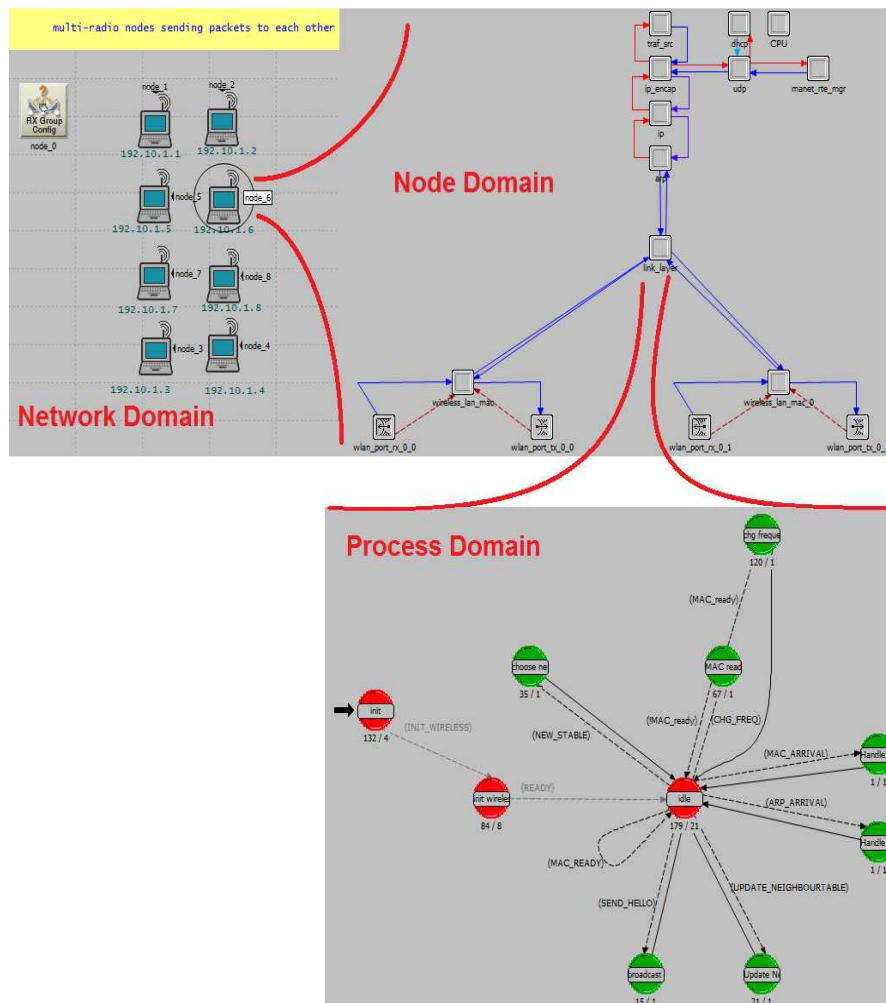


Figure 3.3 - Network, Node and Process Domain (extracted from [4]).

Thanks to object oriented architecture it is possible to model namely any kind of node, link or process which are instances of their models just like objects are instances of classes in the object oriented programming. There are already many predefined models representing real vendors' equipment, existing technologies or protocols. It is possible to define new set of new models, modifying existing ones or creating new from scratch.

Application and user profiles that are used to generate traffic in simulations can be freely defined. End-user devices can generate voice calls, web browsing, database access, file transfer, video conferencing or any other traffic that one can define. Moreover the profile of usage can be defined i.e.

heavy or light web browsing or level of quality for video streaming. User profiles can be named like gamer, basic user, engineer and the traffic generation policy can be added to it. That creates possibilities of modelling the network behaviour in a particular place like school or research institute. Additionally importing traffic data from external files or programs can be done.

The statistics to be gathered from a simulations can be displayed in four distinct forms: output vectors, output scalars, animation and proprietary reports and files. Generally all of the output data can be displayed in the form of graphs, which can be plotted together to allow easy comparison. Before the start of a simulation the statistics to be gathered must be selected from a large list. Each of the module in the nodes can be a source of statistic and choosing one to be gathered triggers the reception of data from a module.

3.6 Implementation in OPNET

Network model as well as the node model presented before is implemented in the simulation software. The node model presented on Figure 3.1 is the base for the implementation in Opet Wireless Suite software. The model presented on the Figure 3.4 is taken from [4]. The original model from OPNET consists of single wireless lan mac interface and was taken as a base for model. The second wireless lan mac was added and the modifications to link layer were done to implement RCA functionalities.

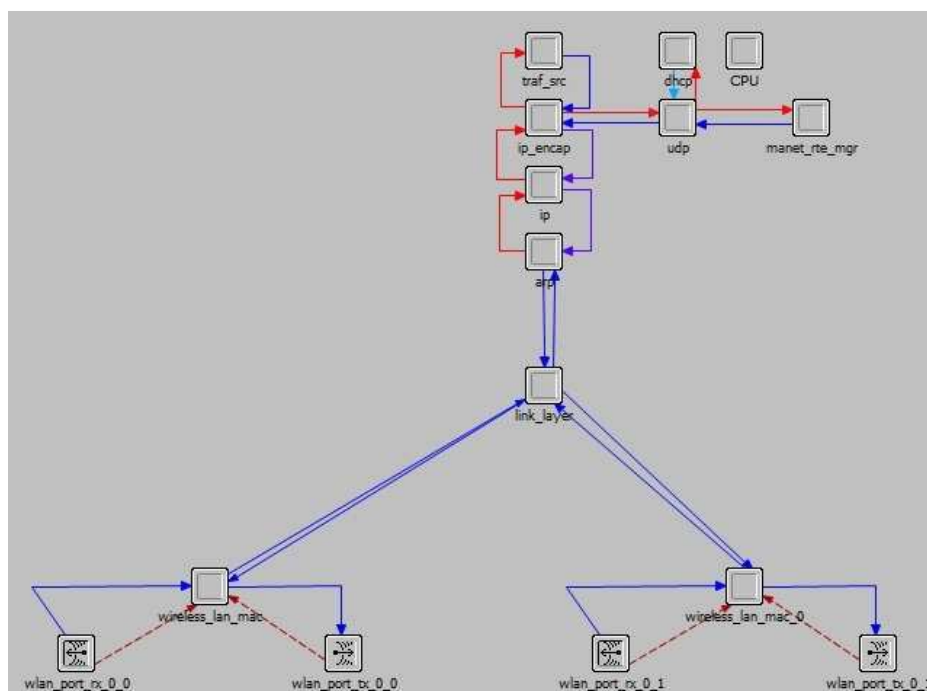


Figure 3.4 - Node model with switchable and fixed interface (extracted from [4]).

The node model without modifications has been adopted from [4] and is shown on Figure 3.4, which:

- Has got 2 interfaces managed by a specially developed link layer that process the packets arriving from higher 3rd layer,
- Uses 802.11a system to forward backbone packets,

- Uses packet generator for generating the access traffic packets emulating traffic received on access interface 802.11g,
- Has got link layer with the channel allocation strategy implemented in such a way that there is no need for ARP and MAC module change. Link layer is responsible for exchanging the packets between ARP module and proper MAC module which represents proper physical interface. The link layer must choose over which interface it needs to transmit the packet. The link layer is playing the role of the ARP. It indicates, for a given next-hop destination IP, which is the corresponding MAC address of the destination. Link layer has got a separate logical queue for each channel that the packets can be transmitted on,
- Has got Neighbour Table with IP address, MAC address and static channel of a node.

RCA allocation algorithm is implemented in the multi-radio node. The implementation includes performing listed activities:

- Each node holds an IPv4 address and is equipped with two MACs,
- The static-MAC has a defined static channel,
- The switchable-MAC switches the channel periodically in a round-robin way,
- Node broadcasts the Hello packets that inform neighbours about its IP address, MAC address and the channel that static-MAC is using,
- When a node receives the Hello packet the MAC address, IP address and static-channel number of a source node of Hello packet are being updated in the Neighbour Table,
- When the packet arrives from ARP layer the next hop destination address is known the static-MAC channel is corresponding to it is recognized so that the packet can be forwarded to proper queue,
- When a packet is received from MAC layer to the link_layer layer it is simply being forwarded to the ARP layer.

Opnet software is not able to simulate variable environment conditions. Due to that many simulations need to be made with following assumptions:

- Backbone and Access Interfaces should operate on different frequencies so there are no interferences between transmissions among backbone nodes and between access users and nodes. Due to above and because access channel issues are not important to backbone network simulations the traffic is being generated in packet generator module,
- Processing and propagation delay is neglectable compared to transmission delay,
- During the whole simulation there is no possibility of using adaptive data rates. The simulator allows only fixed data rates.

In the OPNET simulation software several traffic distribution policies are possible to use. In this work only two of them are going to be implemented. In OPNET traffic distribution describes the period of time between packet generation. It is called *interarrival time*. Two schemes are used in this work:

- Uniform distribution (constant *interarrival time*) assures that interarrival time between packet generation is always exactly the same,

- Exponential distribution (exponential *interarrival time*) when used infers that value of interarrival time of packets is each time randomly generated around mean value. However, when the average value of interarrival times is calculated it equals the interarrival time of uniform packet distribution.

As to possess the reference values to make further evaluation of RCA algorithm maximum theoretical one hop application data rate [25], $R_{T_app_oh_max}$, is being benchmarked using Opnet. $R_{T_mac_oh_max}$ represents theoretical maximum number of MAC Service Data Units (MSDUs) that can be transmitted in a time unit of a second. All of the overheads associated at each sublayer MAC sublayer, Physical Layer Convergence Protocol (PLCP) sublayer and Physical Medium Dependent (PMD) sublayer) are considered and presented on Figure 3.5. Theoretical values are derived from [25] under the following assumptions:

- Bit error rate (BER) is zero.
- There are no losses due to collisions.
- PCF mode is not used.
- No packet loss occurs due to buffer overflow at the receiving node.
- Sending node always has sufficient packets to send.
- The MAC layer does not use fragmentation.
- Management frames such as beacon and association frames are not considered.

It is said that maximum approximation error of $R_{T_mac_oh_max}$ is less than 2% in the worst case. This error is however connected only with the fact that delay per each MSDU is continuous. In the real life situation the losses connected to collisions and packet loss due to buffer overflow decreases the possible to achieve maximum One-Hop rate.

Wireless transmission in Opnet software is presenting significantly higher overhead than it is present in reality. During the initial phase of the packet transmission the PLCP overhead of the packet is sent with the rate of 1Mbps or 2Mbps to assure backwards compatibility with all of the 802.11 systems. The data rate depends on the modulation scheme used. As the simulator is not able to change the data rates during the simulation it needs to increase the size of the MAC packets so that the transmission time of the header is the same. Because the 802.11a is used in the work, only the long PLCP packet header can be used. The size of PLCP overhead is increased, depending on the data rate used and this is sent under the name *bulk size of the packet*. The delay values are kept the same but this creates significant “artificial” overhead which is seen as additional traffic that biases the results.

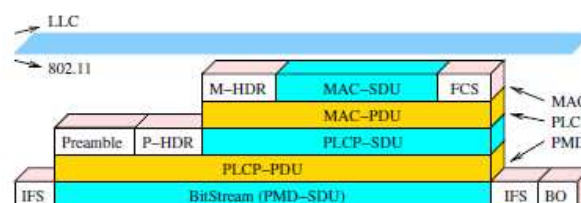


Figure 3.5 - Overhead at different sublayers of 802.11 (extracted from [25]).

To remove the biased traffic connected with the “artificial” overhead following is the equation that when applied to the value of traffic obtained from Opnet removes the value of “artificial” overhead:

$$R_{Op_mac} = R_{Op_bias} \times S_{p_oh} / (S_{p_oh} + S_{PLCP}) \quad (3.18)$$

where:

- R_{Op_mac} is the rate without “artificial” overhead,
- R_{Op_bias} is the rate with “artificial” overhead,
- S_{p_oh} is a size of the packet with normal overhead,
- S_{PLCP} is a size of the “artificial” overhead added to the packet by Opnet.

The maximum one hop transmission range depending on wireless transmission parameters is calculated and is shown in Table 3.1. Using the path loss and link budget equations (3.8), (3.9) and (3.10) and values of: transmitted power is $P_{tx} = 23$ dBm, the frequency $F = 5.5$ GHz of transmission and the $a_{pd} = 2.0$ and $\Delta L = 0$ parameters as the simulations are run in free space environment. The distance is calculated using the minimum received power level, $P_{min}(R)$, so that the maximum range, d_{tx_max} of successful transmission is defined. The theoretical interference distance is calculated based on (3.6).

Some implementation issues regarding OPNET software are revealed in [26]. Those contribute to the higher than expected packet losses in OPNET simulations. When the packet has been received and is being decoded any packet that arrives (exceeds receiver sensitivity) in this time is regarded as interference and results in collision with the reference packet. This should not be like that and the arriving packet should be compared with SINR to decide if it will cause a collision or not. As a result more packets than expected are lost.

Table 3.1 - Maximum d_{tx_max} for P_{tx} of 200 mW, considering various Rates for $d_{n2n} = 100$ m.

Data Rate (R)	$P_{min}(R)$ (received)	d_{tx_max}	$P_{SINR_{min}}$	d_{i_t}
Mbps	dBm	m	dBm	m
6	-82	773	18	794
9	-81	689	21	1 122
12	-79	547	22	1 258
18	-77	435	25	1 778
24	-72	244	25	1 778
36	-70	194	32	3 981
48	-66	123	34	5 011
54	-65	109	35	5 623

Chapter Four

Scenarios And Results

This section, at the beginning provides scenarios description used for all of the studies conducted in this work. The results from the studies are presented later, being grouped by the scenario used for study and subdivided by the parameter under study.

4.1 Scenarios Description

This section provides the description of scenarios under study. At first the chain scenario is described that is followed with ring scenarios. The idea behind the scenarios deployment is to check how the main parameters of the RCA algorithm are influencing the network performance.

4.1.1 Chain Topology Scenario

In each chain scenario topology nodes are uniformly distributed on a line as in Figure 4.1. Nodes are in the distance of d_{n2n} from the former and latter node, transmitting with the same P_{tx} power. One node at the end of the chain is connected to the internet with high capacity link. This link is not going to be analysed. Based on this, values from Table 3.1 are adopted. The packet size, the amount of data that is available for a user is set to 1500B as it is said to be one of the most common packet sizes to be found in internet backbone networks [27].

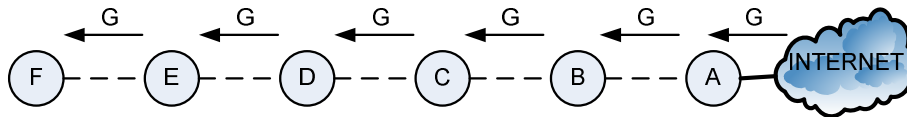


Figure 4.1 - Chain Topology.

The transmission and theoretical interference ranges in the chain topology make the one-hop neighbour nodes be in each other's transmission range. The remaining nodes are in the interference range of a node. For example Node C's transmission range covers Node D and Node B in Figure 4.1, while all other nodes are in the theoretical interference range of Node C. This makes evaluation of number of hops and channel number impact simpler but less realistic. It may often happen, depending on the channel assignment that 2nd hop neighbour uses the same channel and is in the theoretical interference range, what should significantly impact the achieved R_{app} .

Table 4.1 - Parameters Common for Each Scenario.

Frequency start point for 802.11a	MHz	5500
P_{tx}	dBm	23
d_{n2n}	m	100
d_{tx_max}	m	109
d_{i_t}	m	5624
r_{t_gen}	-	100% downlink
Packet size	B	1500
τ_{max}	ms	100
R_{PER_max}	%	1
Data rate	Mbps	54
P_{min}	dBm	-65
Propagation Model	-	physical interference model

As the first chain scenario, the one with one hop and two nodes that use single radio 802.11a interfaces is analysed in order to obtain reference parameter. For each data rate mandatory

supported by 802.11a standard the theoretical values maximum One-Hop application data rate $R_{T_app_oh_max}$ are calculated and Opnet benchmarking simulations are carried out to obtain maximum Opnet One-Hop Application data rate $R_{Op_app_oh_max}$. Gradual increase of the $R_{app_offered}$ is done by decreasing interarrival time of the packets until dropped packets start to appear not exceeding the value of R_{PER_max} . The value of R_{PER} in simulation is obtained by subtraction of received packets from transmitted packet number. Parameters for One-Hop scenario are presented in Table 4.2.

Table 4.2 - One hop scenario parameters.

	Unit	One Hop 6	One Hop 12	One Hop 24	One Hop 54
P_{min}	dBm	-82	-79	-72	-65
T	Mbps	6	12	24	54
N_n	-	2			
N_{ch_ort}	-	2			
N_{ohn}	-	1			
Usage Function	-	Less Used			

Second step is to analyse the degradation of application data rate in the Multi-Hop chain scenario. The number of nodes that chain is composed of is increased by 1 each time, what can be observed in Table 4.3. Starting from 2 hop and 3 nodes and finishing at 5 hops and 6 nodes, as in Figure 4.1. For each chain the value of offered application data rate, $R_{app_offered}$ is increased to find the maximum application data rate, R_{app_max} . It is done by increasing interarrival time while keeping packet size constant. For both single-radio (S-R) and multi-radio (M-R) two indicators are used to evaluate R_{app_max} . Packet Error Ratio (PER) is kept lower than R_{PER_max} and the delay is kept lower than τ_{max} . These both indicators assure that network is reliable in terms of packet delivery and also provides satisfactory quality of service.

Table 4.3 - Chain Scenario Characteristics.

	Unit	Chain S-R				Chain M-R, 2ch				Chain M-R, 3ch				Chain M-R, 4ch				Chain M-R, 5ch			
N_{ch_ort}	-	1				2				3				4				5			
N_n	-	3	4	5	6	3	4	5	6	3	4	5	6	3	4	5	6	3	4	5	6
N_h	-	2	3	4	5	2	3	4	5	2	3	4	5	2	3	4	5	2	3	4	5
R	Mbps	54																			
P_{min}	dBm	-65																			
N_{ohn}	-	2																			
Usage Function	-	Less Used																			

4.1.2 Hexagonal Topology Scenarios

Hexagonal topology consists of nodes that are located at the corners of hexagons laying aside each other. Each node has got a maximum the 3 one-hop neighbours. Nodes are gathered in the sets, called rings. Ring is a group of nodes that is within the same distance from the gateway in terms of hop count, N_{h_gw} . Each ring is assigned the number, $N_r = N_{h_gw}$ equal to the distance of all the nodes to

the gateway as presented in Figure 4.2. The scenarios differ by the number of rings and what is directly implied by the number of nodes as shown in Table 4.4. Parameters in Table 4.1 are applicable to hexagonal scenario as well. The studies are done step by step with analysing the downlink traffic scenarios, uplink traffic scenarios and concluding with bidirectional scenarios being the most realistic ones.

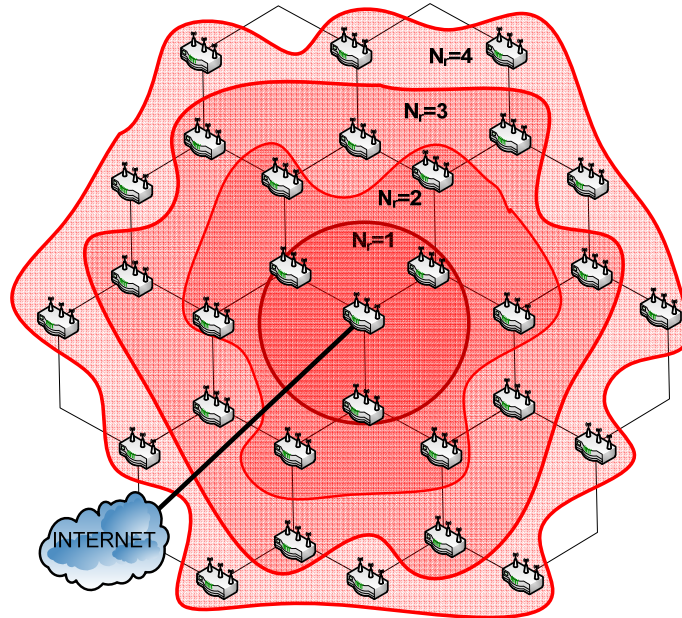


Figure 4.2 - Hexagonal Topologies.

Centre node is a gateway node from and to which all the traffic is heading. The data rate is set to highest possible $R = 54$ Mbps and to assure that only this rate is used a minimum receiver sensitivity P_{min} set to -65 dBm. Example of transmission and theoretical interference ranges are presented in Figure 4.3.

Table 4.4 - Hexagonal Scenarios Parameters.

Scenario	Unit	Reference Hex # 1	Hex # 2	Hex # 3	Hex # 4
N_n	-	4	10	19	31
N_r	-	1	2	3	4
N_{ch_ort}	-	2,3,4		4,7,11	
N_{ohh}	-	3			
P_{min}	dBm	-65			
R	Mbps	54			

Every time the simulation is run the traffic flows are started when convergence time passes, which in many cases is different. The length of convergence time is checked by running 10 simulations, than the longest one is taken as a convergence time. This is done to achieve simulator stability and not to have other factor corrupting the achieved R_{app} . The network is afterwards stable, without other nodes connecting to the network and changing the set channel distribution. If this would not be done, the channel distribution in network would be dynamic. The application data rates achieved by nodes would

be lower as throughout some part of simulation the channel distribution would not be known to all of the nodes. For example, the number of available channels is set to 11, and there are 2 nodes exchanging packets, node A and node B. Node B's static interface is fixed on channel 11, while node A on channel 1. Node A has just changed the static channel to channel 11 and it needs to broadcast this information through dynamic interface on each of the channels. As explained it does it in round robin way, going through each channel. Let it be assumed it starts from channel 1 and must go through all of the channels until 11th. Let it be assumed that node B, a neighbour node wants to transmit to a node A. Through the period when the information about static channel change is being broadcasted node B will not be able to communicate with A, because it still transmits to it via channel 1, which after the change is not valid.

The coverage of transmission range for $P_{tx} = 200\text{mW}$ in ring scenarios is presented in the Figure 4.3. The d_{n2n} distance is kept the same as in chain scenario. As one can observe the node has got maximum 3 One-Hop neighbours inside the transmission range. Some node from the borders of the network may have 1 or 2 One-Hop neighbours. The theoretical interference range of 5.6km makes all other nodes from the network vulnerable to the transmission on the same channel as the considered node. This is why the theoretical interference ranges are not marked on the figures.

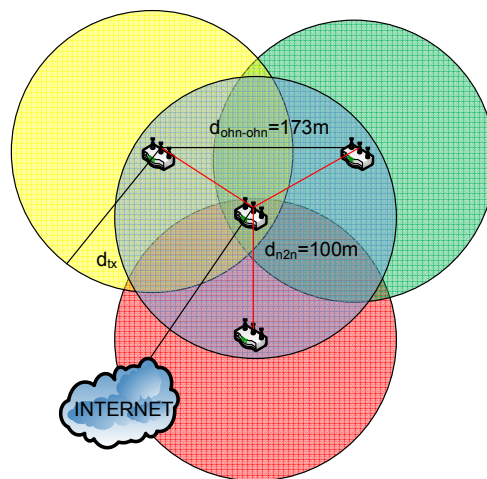


Figure 4.3 - Topology illustrating d_{tx} range in 1 ring scenario.

For each of the simulations the simulation time was 1 minute with 10 different seeds. The convergence time has been adjusted varying from 30s to 120s.

4.2 Chain

The following section presents the results from the Chain topology scenario studies. First the single hop benchmark results are presented, where the maximum capacity of single radio link is measured. Next the radio access method CSMA/CA with and without RTS-CTS mechanism is evaluated in terms of possible to forward application data rate. As a next step the study of interference range in OPNET is presented. The last study made on chain topology is number of hops and number of channel study.

4.2.1 Single hop benchmark

The first study is the assessment of OPNET simulator in order to possess the reference value for further analysis. The scenario is One-Hop chain, with 2 nodes, where one is sending to the other. The 4 data rate rates mandatory supported by 802.11a system are analysed. The aim of this study is to benchmark the output of simulator for defined data rates defined by the standard. One-hop scenario is done with $R_{PER,max}=0\%$ as the theoretical values were calculated with the same assumption.

Theoretical calculations of application data rate per one hop, $R_{T_app_oh_max}$ are based on [25]. The paper presents the method which discards the protocol overheads of first 3 layers of ISO/OSI stack, leaving the 4th layer application data rate. Moreover the method takes into account the overhead connected to ACK messages, DIFS and SIFS periods in CSMA/CA. For RTS-CTS the same issues are taken into account followed by RTS, CTS and backoff time overheads. The proposed method is adjustable to various MAC schemes, spread spectrum technologies and various data rates that are used in 802.11 group of standards. The accuracy is said to be 2% at most. Important assumptions for the calculations are:

- BER is zero,
- There are no losses due to collisions,
- No packet loss occur due to buffer overflow at receiving node,
- Sending node has always got sufficient packets to send.

In the Table 4.5 the results from study are presented. Opnet values are different than theoretical results. The results from first three cases are fitting into the 2% accuracy of theoretical considerations. For the last case, for 54Mbps of R_{NB} the worse OPNET performance is software specific. The study to explain this issue may be conducted in the future.

Table 4.5 - One-Hop simulation results for packet payload of 1500B

R_{NB} of PHY interface of 802.11a system	Theoretical		Opnet		Opnet decrease to theoretical value
	$R_{T_app_oh_max}$	Approximation Error	$R_{Op_app_oh_max}$	Std. Dev.	%
Mbps	Mbps	%	Mbps		
6	5.33	2	5.29	0.0010	0.7
12	10.00	2	9.84	0.0010	1.6
24	17.71	2	17.39	0.0008	1.8
54	31.15	2	30.00	0.0040	3.7

4.2.2 Traffic distribution and Access Method

Next study is made to compare the transmission schemes and traffic distribution influence on R_{app}

achieved. One-Hop scenario with 2 nodes is used. This is also benchmarking study to obtain application data rate differences for CSMA/CA with RTS-CTS and without it. To analyse usefulness of RTS-CTS method the separate ring study is conducted and presented later.

As shown in Table 4.6, application data rates vary depending on the collision avoidance schemes used. Compared to CSMA/CA without RTS-CTS when the CSMA/CA with RTS-CTS mechanism is used additional overhead is present i.e. RTS, CTS messages that needs to be transmitted with lowest data rate possible. This creates additional high delays per packet which results in lower overall performance on one link compared to CSMA/CA without RTS-CTS.

The uniform and exponential traffic do not differ as the link-layer model, in current version have infinite buffers implemented. This allows packets to have higher delay and still be transmitted. Simulations are run with the same quality indicators as before $R_{PER_max}=0\%$ and $\tau_{max}=100ms$.

For a studied application data packet (1500B) based on [25] and in Table 4.7 the delays for sending a single packet are presented. Decrease of application data rate of CSMA/CA with RTS-CTS compared to CSMA/CA without RTS-CTS is because of more control packets and inter frame spaces. In pure CSMA/CA the only control packet is ACK, and periods IFS of SIFS, DIFS and BO period. In CSMA/CA with RTS-CTS there is ACK, RTS, CTS and the periods of 3xSIFS, DIFS, BO. This means that 2 more packets must be sent (RTS, CTS) and 2 more IFS (2xSIFS) must be waited by transmitting nodes. This increases the delay, which causes the application data rate to decrease compared to CSMA/CA without RTS-CTS as it is presented in the Table 4.6. The benefit of using RTS-CTS is analysed and discussed as a simulation scenario later.

Table 4.6 - Traffic distribution and Access Method influence on one-hop application data rate.

Access Method	Traffic Distribution	Max Application Data Rate			
		Theoretical	Achieved	Std. Dev.	Theoretical to Achieved loss %
CSMA/CA without RTS-CTS	Uniform	31.15	30.00	0.004	3.7
	Exponential		30.00		3.7
CSMA/CA with RTS-CTS	Uniform	26.60	24.49	0.001	7.9
	Exponential		24.49		7.9

Table 4.7 - Delay Comparison of Access Methods for Packet size of 1500B and 54Mbps (extracted from [25]).

Scheme	Delay Components [μs]							
	τ_{DIFS}	τ_{SIFS}	τ_{BO}	τ_{RTS}	τ_{CTS}	τ_{ACK}	τ_{DATA}	τ_{total}
CSMA/CA without RTS-CTS	34	9	67.5	N/A	N/A	24	250.63	385.13
CSMA/CA with RTS-CTS	34	9x3	67.5	24	24	24	250.63	451.13

4.2.3 OPNET Interference Range Benchmark

As in the simulation scenarios nodes using the same static channel are situated in various ranges from each other the influence of interferences is measured on the packet loss. As presented on the Figure 4.4 two pairs of nodes are in this scenario. Node A is transmitting to Node B and Node C is transmitting to Node D. The data rate considered is highest possible $R=54\text{Mbps}$, that demands high $\text{SINR}=35\text{dB}$. The nodes are set to communicate on the same channel, with the same $R_{app\ offered}$. The distances between the nodes are set the same as in the chain and ring topologies $d_{n2n}=100$. The distance between the Node B and C is the node to interferer distance d_{n2i} , which is being increased until theoretical max interference range of 5.62km. Distances peculiar to ring topology are analysed as presented on Figure 4.6.

The results are presented on the Figure 4.5. The $R_{app}=20\text{Mbps}$ so that the wireless links are congested and the collisions are easily spotted. As one can observe if the nodes in the network are using the same channel, at the distance 1000m from each other the packet loss is at the level under maximum allowed PER, being 0.49%. This is the main reason for a high difference between OPNET interference range and the theoretical calculated one. In OPNET some packet loss is allowed, while in theoretical calculations no packet is allowed to be lost. The OPNET interference range for $R=54\text{Mbps}$ is $d_{i_o} = 1000\text{m}$.

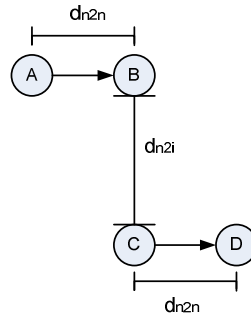


Figure 4.4 - OPNET Interference Range Benchmark Topology.

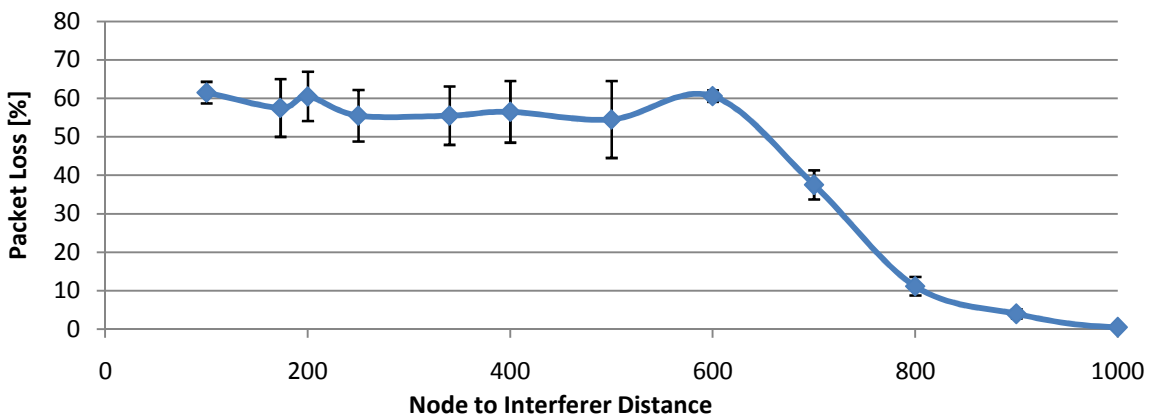


Figure 4.5 - Packet Loss for Various Node to Interferer Distance.

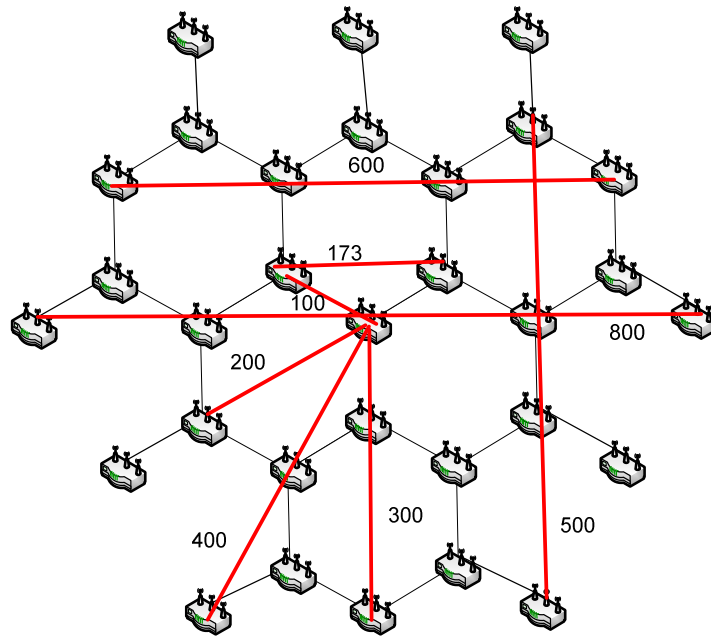


Figure 4.6 - Peculiar distances in meters for Ring Topology.

4.2.4 Number of Hops vs. Number of Channels

The methodology of work conducted to obtain the results is presented in following. For each chain (1-5 hops) the offered application data rate is being increased. Moreover in each chain there is increasing number of orthogonal channels available to choose from by the node when assigning channel to a static interface. As one can see on Figure 4.7 the more channels there are the higher achieved application data rates as the interference levels are decreasing. The main rule is that with higher available number of channels fewer nodes transmit on the same channel simultaneously causing fewer collisions.

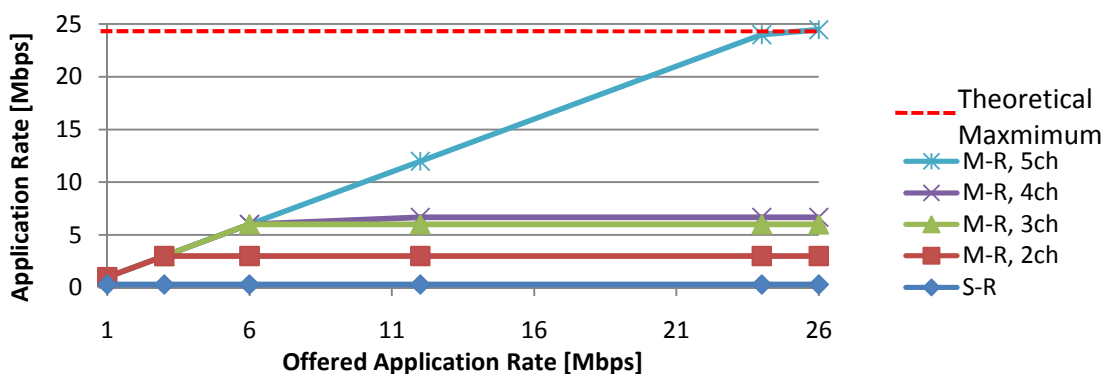


Figure 4.7 - Achieved Application Data Rates in Chain:4 hops scenario.

In Multi-Hop Chain Scenario studies the quality indicators are to be kept under $R_{PER_max} \leq 1\%$ and delays are kept under $\tau_{max} \leq 100ms$. R_{PER_max} allow some packets being dropped this time as to simulate realistic scenario. In each of the following studies, both in chain scenario and ring scenario those values are kept the same. In Chain Scenario studies the value of R_{app} achieved by each node is the highest value that when applied assures that quality indicators are not exceeded.

When a study is carried out, the interarrival time of the packet is decreased to find maximum value of Application Data Rate that assures Maxmin Fairness. The function of Application Data Rate to Interarrival time is presented on Figure 4.8. For a studied packet size of 1500B the function is (4.1).

Equation for application data rate, for packet size of 1500B:

$$R_{app[\text{Mbps}]} = \frac{S_p[\text{b}]}{1000000} \times R_{int[\text{s}]}^{-1} \quad (4.1)$$

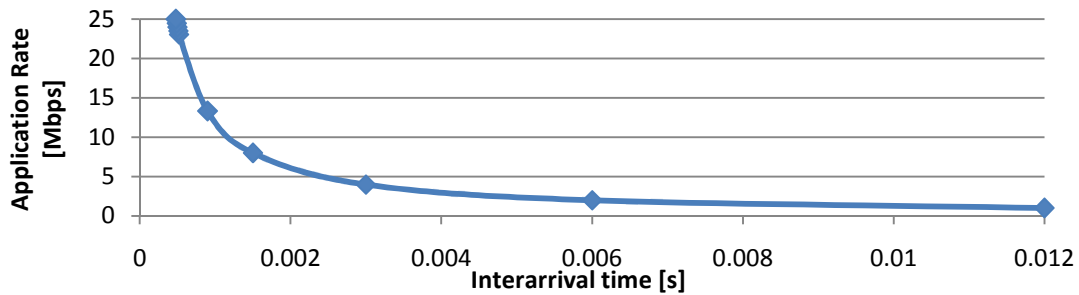


Figure 4.8 - Application Data Rate vs. Interarrival Time.

To obtain the results both delay and PER must be kept below 100ms (delay) and below 1% (PER). The sum of those two conditions must be true. For example 3 hops, 5ch M-R Chain Topology Study is presented on Figure 4.9 and on Figure 4.10 the PER increase is presented. The values for application data rates below 23Mbps are omitted as they do not carry significance. The process is as follows. The application data rate is increased by decreasing the interarrival time of the packet with step of 0.00001s, which at this point is equal to 0.48Mbps increase of application data rate each time. As one can observe for $R_{int} = 0.00050\text{s}$ the application data rate is 24Mbps, while for $R_{int} = 0.00049\text{s}$ the application data rate is 24.48Mbps. For the former value the both quality indicators are kept under the maximum values, while for the later one the PER quality indicator exceed the maximum allowed 1%. Although the delay for these values is kept under maximum 100ms, this value is not taken as maximum application data rate. The last value fulfilling the quality conditions $R_{app} = 24\text{Mbps}$ is picked up as the maximum application data rate.

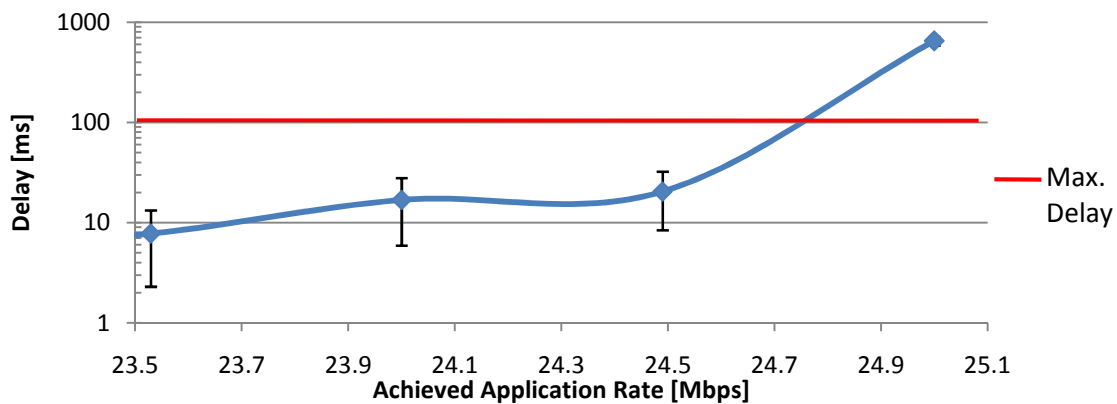


Figure 4.9 - Delay Quality Indicator for 3 hops, 5 channels.

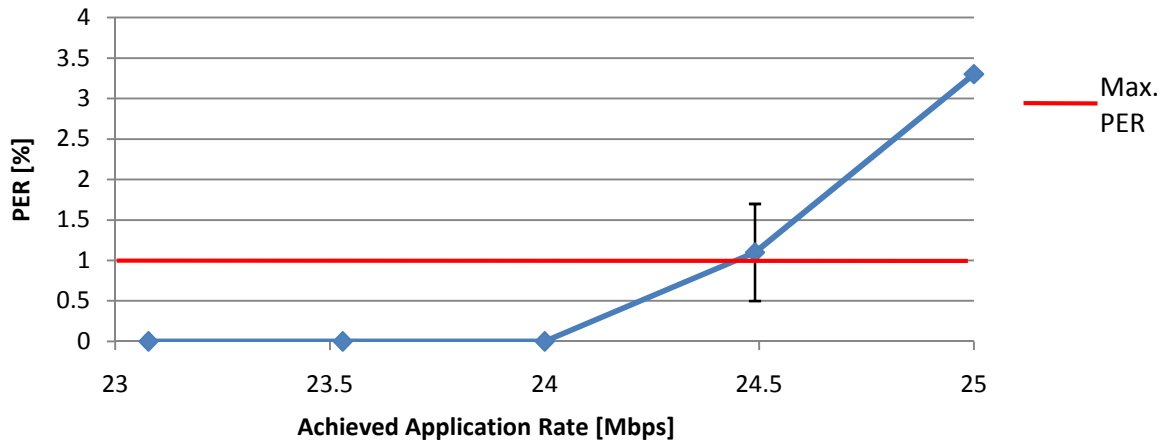


Figure 4.10 - PER Quality Indicator.

Number of hops and Number of channels

Results from the Multi-Hop scenario analysis are presented on the Figure 4.11. The results vary depending on the number of channels used. The general rule is that when $N_h \geq N_{ch}$ the degradation of application data rate is present, that happens as when the same frequency is reused in the neighbourhood interference range. Degradation of Single-Radio (S-R) chain is observed due to multihop environment where the traffic received is declining with average rate of $1/N_h$ [1]. This happens also because the RTS-CTS handshake coupled with virtual carrier sensing (using a NAV) suffers from the problem of link layer congestion [15].

In all of the following results one must remember that traffic is a single unidirectional downlink flow of packets that are sent from the gateway to the last-hop node. The results taken are average values from results of simulation with 10 seeds.

For Multi-Radio utilizing 2 orthogonal channels (M-R, 2ch) the application data rate degradation starts at the point where packets need to pass 3 hops route using 2 channels. Assuming Node A in Figure 4.1 is a source and node D is a destination, the same channels are used by nodes B and D as static channels used for reception. This causes that both are in interference range of each other, experiencing co-channel interference, causing collisions just as in S-R chain.

For a M-R, 3ch chain let us assume the ideal channel distribution i.e. node A is using channel Ch1, B-Ch2, C-Ch3, D-Ch1, E-Ch2. When node D sends packets to node E it is doing that via switchable interface that is tuned into channel Ch2 at that moment, the collisions occur at node B which is in interference range of node D and is receiving packets on channel Ch2, just like the node E. This is the hidden node problem, and the RTS-CTS mechanism is not helpful. The nodes using the same channel are too far away from each other to successfully receive handshake messages. For example node E will not receive neither RTS from node A, nor CTS from node B when transmission A-B is being started.

The case of M-R, 4ch experiences the degradation of signal as well. This happens because of two reasons. Former one is present when the channel distribution is ideal i.e. node A uses channel Ch1, B-Ch2, C-Ch3, D-Ch4, E-Ch1, F-Ch2. When a node C is sending acknowledgements to a node B it

does it via channel Ch2. Node E wants to send the packets to node F on the channel Ch2 as well but as it is sensed as busy the node defers the transmission. This is known as deaf node problem.

Later reason is similar to the M-R, 3ch chain case. As the RCA is assigning the channels using the less used channel in neighbourhood there is no guarantee that the channel which the neighbouring node is using will not be picked up when it is used the same amount of times as other one in neighbourhood. Choosing closer channel causes high interference just like in single radio scenario. The algorithm is not taking into account the distances to the nodes using particular channels which are rated as equal.

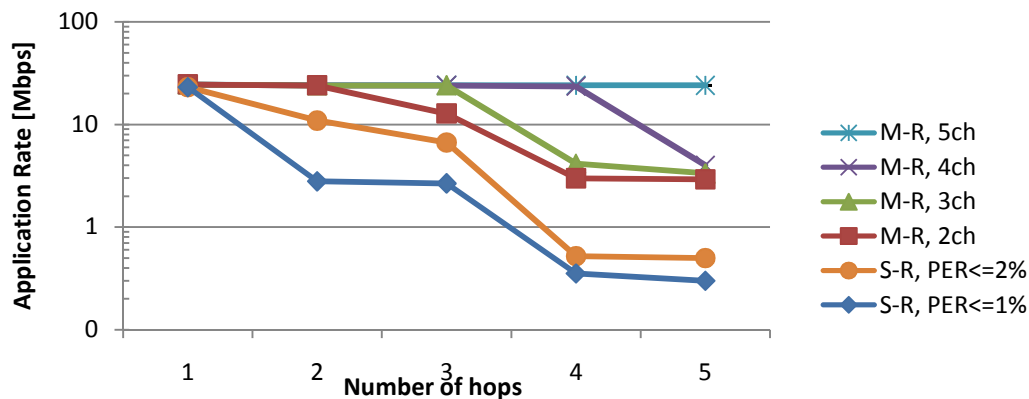


Figure 4.11 - Maximum Application Data Rate vs. Hops Number for Chain Topology Scenario.

For the curve of 5 channels and 5 hops the value of R_{app_max} is kept all the time almost at the level of $R_{Op_app_oh_max}$. This is because there is orthogonal channel available for each hop, which induce that whole chain can be regarded as single point-to-point link. The difference to one-hop scenario is that the delays regarding RTS-CTS mechanism are increased the order of hop counts which result in decrease of R_{app_max} compared to $R_{Op_app_oh_max}$.

The fact that M-R, 5ch chain is allowing maximum application data rate to be forwarded is because each node receives on orthogonal channel. The GW node may be reusing the same static channel as one of the nodes in the chain but this do not cause any packet loss as only the downlink traffic is considered. Moreover in practice, this peculiar situation of assigning orthogonal channel to each receiving node does not happen always. On contrary it often happens that some channels rated likewise may be reused closer than 5 hops away from each other, causing interferences and collisions. The results from such scenarios are presented in Figure 4.12. This was already explained together with $K_Neighbourhood$ parameter explanation and is proving the theoretical considerations presented there.

Longer chains using 5 orthogonal channels should result in the same values as pessimistic M-R, 5ch. This is happening as each channel reused inside OPNET interference area by at least 2 nodes will cause packet loss, when the simultaneous transmission will be scheduled.

Few examples are explained in following. When a 2 hops, 2 channels chain is taken into consideration the chain is built from 3 nodes only. Let it be assumed that Node A, Figure 4.1, assigned Ch0 to static

interface, Node B assigned Ch1 and the channel assignment is being carried out by a Node C. The RCA rates both channels as equally utilised and with the same probability (LU) assigns both channels to static interface of Node C. When a Ch0 is assigned the performance is as presented on the Figure 4.11 $R_{app}=24\text{Mbps}$, while when the Ch1, the same as Node's C One-Hop neighbour is assigned the performance goes down 50% to $R_{app}=12\text{Mbps}$. This is happening as the simultaneous transmissions cannot be scheduled from Node A to B and from Node B to C as it is made on the same channel and while one is transmitting the other sets NAV vector and awaits the wireless medium to be free.

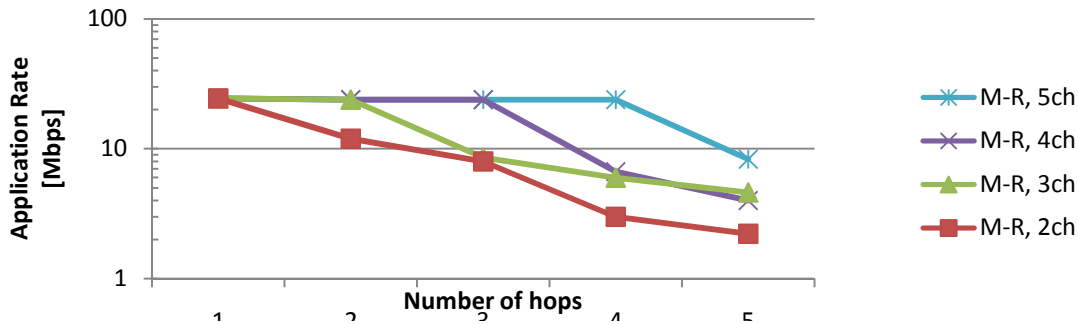


Figure 4.12 - Application Data Rates for Various Scenarios- The Pessimistic Cases.

Next case is case of 3 hops, 3channels where the RCA can make the same wrong decision while assigning the static channel. Let it be assumed that 3 nodes out of 4 have already channels assigned: Node A- Ch0, Node B- Ch1, and Node C-Ch2. The Node D is performing the channel assignment and as $K_Neighbourhood=4$ it is aware of all the nodes' channel assignment. Again the decision of assigning the channel may be better or worse. In the case when channel Ch2 is assigned the situation has been explained in paragraph before. When channel Ch1 is assigned the RTS-CTS exchanged by the nodes A and B cannot be received by Node D so it is not aware of ongoing transmission and Node C can start transmitting to Node D. This will result in many collisions as nodes B and D receiving on the same channel are only 200m away from each other. As one can observe from Figure 4.12 the decrease in the performance is higher than in 2hops, 2channels case because of collisions and retransmission consume more bandwidth than blocking the transmission by setting NAV vector. The best choice in 3hops, 3channels scenario is for the Node D to fix static interface on channel Ch1. This allows for maximum performance as this channel, in unidirectional DL traffic case, is not used for reception as it is gateways channel, which only transmits packets and do not receive them.

The later decrease in performance of M-R, 3ch case is because 3channels reused in the chain of 4 or 5 hops guarantee that the same channel will be reused by at least 2 nodes in the chain. This, connected with the fact of Opnet interference area of 1000m implies collisions and decrease of performance.

Analogical cases of better and worse performing channel assignments can be observed for 4hops, 4channels case and 5hops, 5 channels case as well. The general issue is that when one of the nodes evaluates the usage of other channels equally, it picks up the random channel to assign. This however does not consider the distance between the node that picks up the channel and the other node that uses the same channel. This has got significance are explained before.

As in all of the scenarios only the downlink is used the interferences mentioned before are not the highest possible. When a bidirectional traffic is being used results of R_{app} are presented in Section 4.3.6, and the performance is worse compared to unidirectional traffic. The main reason for that is fact that each node transmits only to one static interface i.e. to one channel. In bidirectional scenario each node (except border ones) would be transmitting to 2 neighbouring nodes almost doubling the interferences in the whole network. Practically speaking in 5hops unidirectional scenario there are 5 active receiving interfaces and 5 active transmitting dynamic interfaces, while in unidirectional traffic scenario there would be 6 active receiving interfaces and 6 active transmitting ones.

4.3 Ring topology

4.3.1 Power Level

In the following studies the impact on performance of the network of three different transmission power levels is analysed. Power levels directly influence the transmission range d_{tx} , according to the (3.8), (3.9), and (3.10). Distance between the nodes, $d_{n2n}=100m$ is not being changed during the study. 7 orthogonal channels have been chosen for this study as 11 would not show the difference in 2 ring scenario. Only the downlink traffic is being analysed. In the scenario the $d_{i_o} = 1000m$ for the $R_{NB} = 54Mbps$ and $P_{SINR_{min}} = 35dBm$. All of the ranges are presented on the Figure 4.13. The first $P_{tx} = 200mW$, so that $d_{tx} = 109m$ with aim to be little bit larger than d_{n2n} . The useful signal covers only One-Hop neighbours. The intermediate power level $P_{tx} = 530mW$, is set so that $d_{tx} = 178m$. With this transmission power level the signal covers the neighbours 2 hops away from a particular node. This will impose that RTS-CTS messages will be received by more nodes and the concurrent transmissions which would result in collisions will not be scheduled. The $P_{tx} = 1000mW$ is set as the maximum value, where $d_{tx} = 244m$ and the coverage of the useful signal reaches nodes 3 hops away from the particular node. All of the ranges are presented on the Figure 4.14 with trend equation and correlation coefficient in Table 4.9.

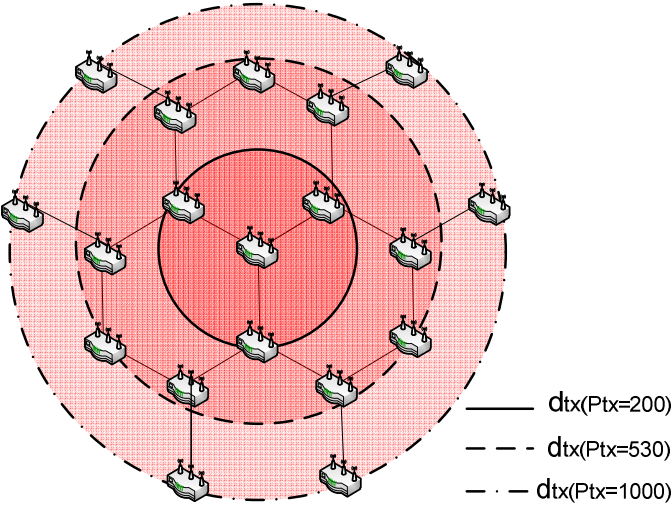


Figure 4.13 - Transmission Ranges For Various Transmission Power Levels.

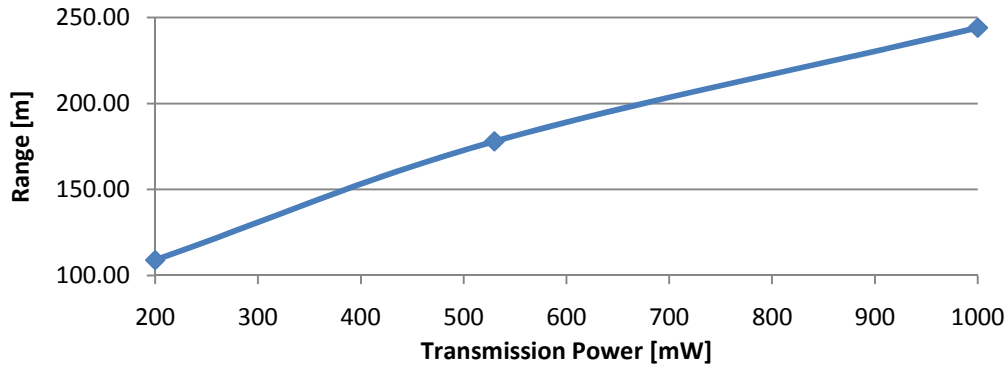


Figure 4.14 - Transmission Power vs. Transmission Range.

The values of achieved R_{app} are presented in Table 4.8 and on Figure 4.16. As one can see there are little differences in between the values of achieved application data rate for 2 rings scenario. The achieved value of $R_{app}=2.67\text{Mbps}$ is 98.1% of the theoretical maximum value R_{t_app} for the lowest value of transmission power. With the increase of transmission power the application data rates drop to $R_{app}=2.61\text{Mbps}$ and $R_{app} = 2.55\text{Mbps}$ which are 95.9% and 93.8% of R_{t_app} for the 530mW and 1000mW of transmission power respectively. With the P_{tx} increase, the d_{tx} range increase and more nodes get to know about the scheduled transmission by successfully receiving RTS-CTS messages. This has got two implications. First is that as more nodes know about transmissions the collisions are avoided, as it can be seen from PER decrease presented in the Table 4.8. On the other hand however nodes are able to transmit less packets. For example, when 200mW is used Nodes D and C, Figure 4.15, can transmit to E or G simultaneously on the same channel. When the power is increased this transmission is blocked, because of RTS-CTS messages reception. In other words, with lower transmission power it was possible to schedule the simultaneous interfering transmissions which although resulted in more corrupted packets, also increased the achieved application data rate. With highest power it is not possible to do so, what decreases packet loss but decreases the application data rate per each user as well.

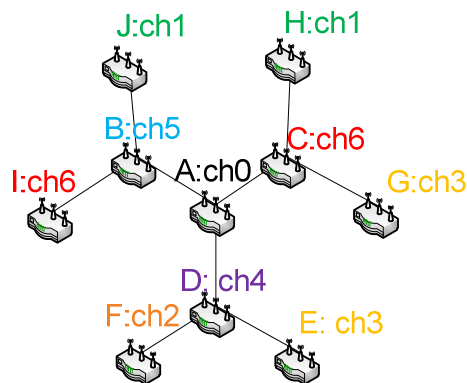


Figure 4.15 - Channel Assignment in Power Study for 2 Rings Scenario using 7ch.

When a 3 ring study is considered the application data rate increases with each power value increase. For a $P_{tx} = 200\text{mW}$, the R_{app} is 0.75Mbps, which is 55% of $R_{t_app}=1.36\text{Mbps}$. For a 530mW and 1000mW of transmission power the values are 89% and 90.9% of theoretical maximum application

data rate. Increase is because many nodes 2 hops away are using the same static channel and the power increase covers those nodes with RTS-CTS messages. It results in coordinated transmissions not colliding with each other and the increase in the application data rate achieved.

Table 4.8 Application Data Rates and PER for Various Configurations.

power	Application Data Rate		
	rings		
	2	3	4
200	2.67	0.75	0.01
530	2.61	1.21	0.01
1000	2.55	1.24	0.5
packet loss		%	
200	0.3	0.70	8.6
530	0.0	0.03	10
1000	0.0	0.00	0.4

In a 4 ring study, for the first two values of transmission power the performance, $R_{app} = 0.01\text{Mbps}$ is at 1.5% of theoretical maximum $R_{t_app}=0.81\text{Mbps}$. This is because large interference range in Opnet $d_{i_o} = 1000\text{m}$ and fact of reusing only 7 channels in 31 nodes network. This infers that several nodes are transmitting simultaneously on the same channel, without knowing about it. It happens as the RTS-CTS messages are not being received due to low transmission range. For 200mW and 530mW only the nodes 1 or 2 hops away can be notified, while the nodes using the same channel are mainly situated 3 or 4 hops away from each other. That is why for the P_{tx} of 1000mW the increase in performance of the network is present. The transmission range increase, result in nodes receiving RTS-CTS messages and because of it the application data rate rise to 58% of the R_{t_app} comes from. As one can see from PER the only usable configuration in 4 ring scenario is $P_{tx} = 1000\text{mW}$.

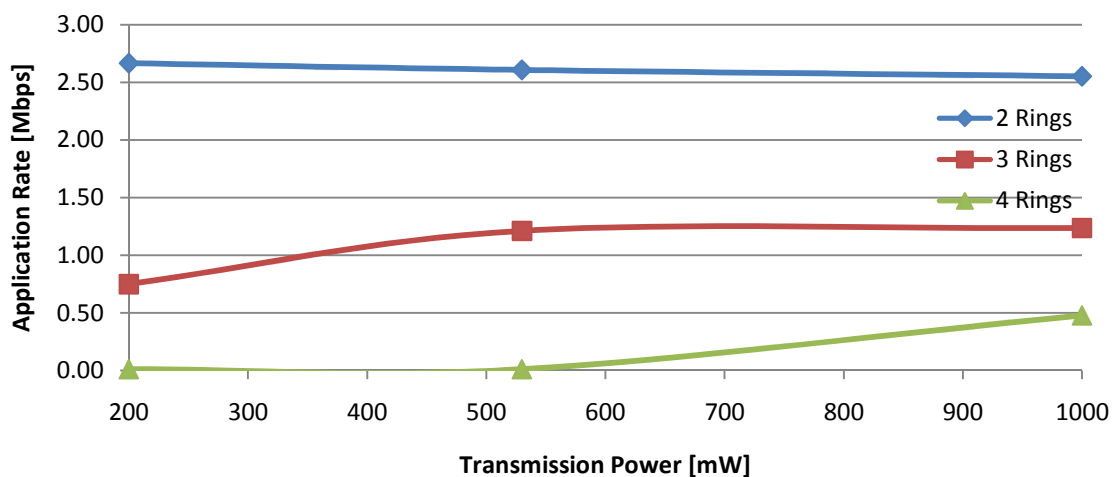


Figure 4.16 - Various Ring Scenarios in Power Study

Table 4.9 - Trend Equations and Correlations - Transmission Power.

Transmission Power vs.:	Equation	R^2
Transmission Range	$d_{tx} = 7.675 \times P_{tx}^{0.5}$	1
Application Data Rate - 2 Rings	$R_{app} = 7 \times e^{-8} \times P_{tx}^2 + 2.709$	1
Application Data Rate - 3 Rings	$R_{app} = -2 \times e^{-6} \times P_{tx}^2 + 0.002 \times P_{tx} + 0.291$	1
Application Data Rate - 4 Rings	$R_{app} = e^{-6} \times P_{tx}^2 + 0.149$	1

For all the transmission powers the RTS-CTS effectiveness is presented on Figure 4.17. This is theoretical value based on [28] and equation (3.6). The size of the area which can successfully receive RTS-CTS messages is larger (the d_{tx} is larger) when the transmission power increases under the assumption of fixed d_{nzn} distance. Only with the highest effectiveness the 4 ring network is usable.

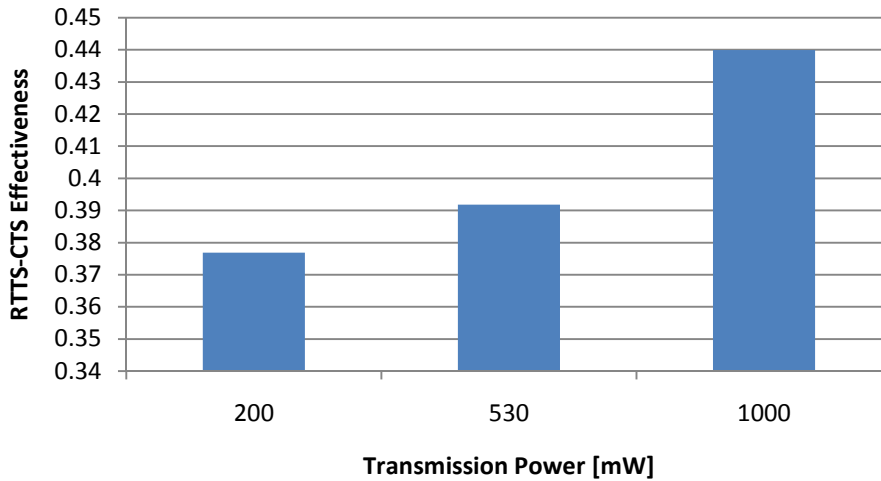


Figure 4.17 - RTS-CTS Effectiveness for Various Transmission Powers.

The results from PER study are presented on Figure 4.21. For the highest $P_{tx}=530\text{mW}$ the PER is 10% and is higher than for $P_{tx}=200\text{mW}$, where PER=8.6%. This is because nodes using the same channel are more than 2 hops away (what P_{tx} covers) and the power increase from 200mW to 530mW does not make them receive RTS-CTS messages. It results however in increase of the interferences received by the nodes as they are not able to receive the packet successfully. The nodes are considering it as a noise or interference. This is confirmed by the 1000mW PER=0.4%, where the nodes that were not able to receive the packets successfully for 530mW are able to do that. What can be observed more is that together with P_{tx} increase from 200mW to 530mW the PER increase, as the interference signal is increased as well. This disadvantage can be overcome only when the power is increased enough so that satisfactory number of nodes can receive RTS-CTS messages.

Delay study is presented in Figure 4.19, and the standard deviation values are presented in the Table 4.10. All of the delays presented are average values of all the received packets by all the nodes in the network. As one can observe the higher the transmission power is the lower the delays become. This is connected with the better performance of the network, explained before, resulting in lower

retransmission count. The trend equations and correlations are presented in Table 4.11.

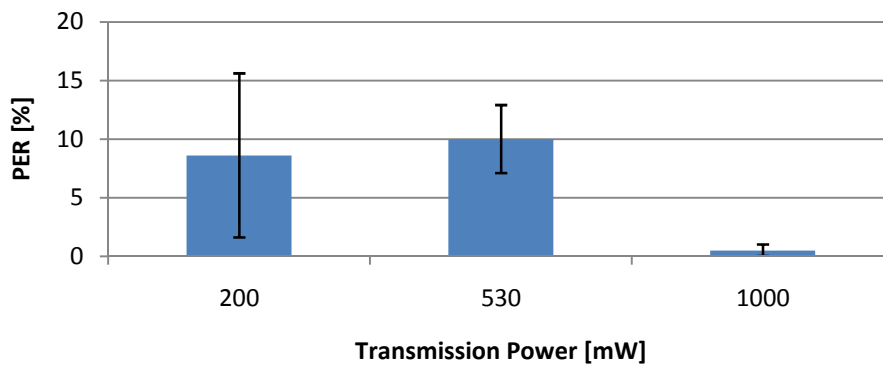


Figure 4.18 - PER in 4 Rings Scenario.

Delays for 3 ring topology are lower than those in 2 rings topology. This is because the same number of channels is distributed among larger number of nodes what allows decreasing the number of collisions and retransmissions.

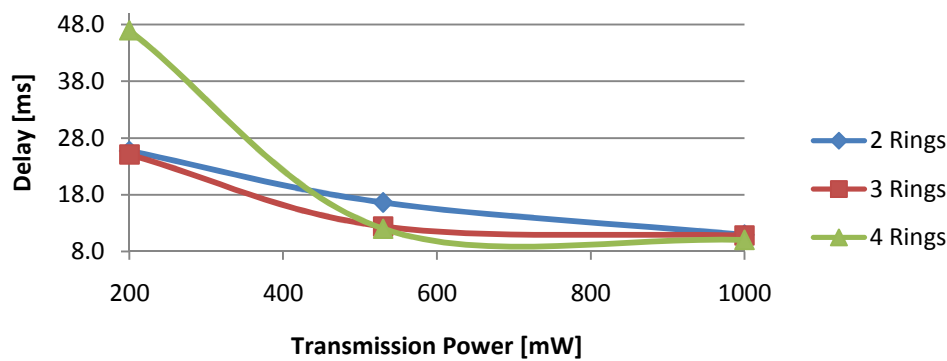


Figure 4.19 - E-2-E Delay for Various Scenarios.

Table 4.10 - E-2-E delay standard deviation values.

power	e-2-e deviation		[ms]
	2 Rings	3 Rings	4 Rings
200	5.0	5.0	26.0
530	2.0	8.0	1.6
1000	1.0	9.0	2.0

Table 4.11 - Trend Equations And Correlations - Transmission Power vs. Delay.

Transmission Power vs.:	Equation	R^2
Delay - 2 Rings	$\tau_{e2e} = -9.2 \ln(P_{tx}) + 74.44$	0.999
Delay - 3 Rings	$\tau_{e2e} = 4 \times e^{-5} \times P_{tx}^2 - 0.070 \times P_{tx} + 37.44$	1
Delay - 4 Rings	$\tau_{e2e} = -0.199 \times P_{tx} + 81.70$	1

As the high packet loss has been observed in 4 ring topology studies the adjustment of interference distance and its impact over the performance of the network has been studied. All mandatory supported in 802.11a data rates have been checked. 4 ring scenario has been adopted for this study with constant $d_{n2n}=100\text{m}$. Together with data rate the values of $P_{min}(R)$, P_{tx} and $P_{SINRmin}$ have been changed to keep transmission range $d_{tx}=109\text{m}$. The values of changeable parameters are presented in the Table 4.12. The theoretically calculated interference distance is presented on the

Table 4.12 - Parameters in interference distance study.

data rate	Mbps	6	9	24	54
$P_{min}(R)$	dBm	-82	-81	-72	-65
$P_{SINRmin}$	dBm	18	21	25	35
P_{tx}	mW	4	5	40	200

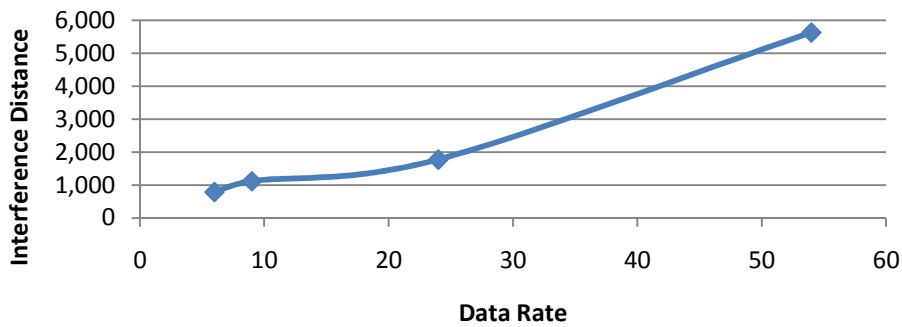


Figure 4.20 - Theoretical Interference Distance for Various Data Rates.

As the performance of the 4 rings network still was not satisfactory, for each data rate studied the interarrival time was set the same, and the $R_{app\ offered}=0.012\text{Mbps}$ has been deployed. The performance results are presented in the Table 4.13 showing that for each of the data rate and what follows each of the interference distance the same not satisfactory performance is present. It is not possible to use lower interference distance as it is no possible to use in 802.11a lower data rate than 6Mbps. What is concluded is that using freespace propagation and $a_{pd}=2$ the interferences will always be present in the studied hexagonal topologies.

Table 4.13 - Performance of 4 Ring Network for Various Data rates and Interference Distances.

Data Rate	Mbps	6	9	24	54
d_i	m	794	1 112	1 778	5 623
R_{app}	Mbps	0.012	0.012	0.012	0.012
Packet Loss	%	13	13	13	10

4.3.2 Handshaking Effectiveness

The next study is comparison between access schemes of CSMA/CA with RTS-CTS and CSMA/CA

without RTS-CTS. It is done, based on 2 rings scenario, where P_{tx} is set to 200mW, maximum number of channels is set $N_{ch} = 11$, UF is WLU, $k_{neighbourhood}$ parameter is set to 4. All of those parameters should allow maximum R_{app} to be achieved and evaluate both access methods for different traffic characteristics. The 4 cases are studied. Those are extracted from [24]:

- 100% DL traffic,
- 100% UL traffic,
- 50%/50% UL/DL traffic,
- 25%/75% UL/DL traffic.

Since there is 11 orthogonal channels to choose from and 10 nodes to assign those channels to, the interferences are kept at minimal level.

Results of the study are presented on Figure 4.21. The first study is 100% UL study, where using RTS-CTS results in $R_{app} = 2.26\text{Mbps}$, while without RTS-CTS $R_{app} = 0.86\text{Mbps}$. Considering UL case all of the traffic is heading to central point-gateway. This means that nodes farther away transmit to the ones that are closer i.e. 2nd ring nodes transmit to 1st ring nodes and 1st ring nodes to the gateway. This means that each time 2 or 3 nodes are transmitting on the same channel to reach the static interface of the receiver. For example as on Figure 4.22 (a), nodes A and B benefit from RTS-CTS coordination as they transmit on the same channel to node C (the colour of the arrow represents the channel that the dynamic interface is transmitting on, while the node's letter represents the channel assigned to static interface). Nodes F, C and E also benefit from RTS-CTS when transmitting to node D. In this case using coordinated access of RTS-CTS is clearly advantageous as all the transmissions can be scheduled, what helps to avoid collisions.

Without the RTS-CTS mechanism nodes are not aware of transmissions ongoing around. Nodes are trying to schedule the connection at the same time that other ones are transmitting. As the d_{tx} is set that only one-hop neighbours can sense the medium, the nodes C and E from Figure 4.22(a) are not aware of Node F transmitting to D. This is hidden node problem, for which RTS-CTS has been developed.

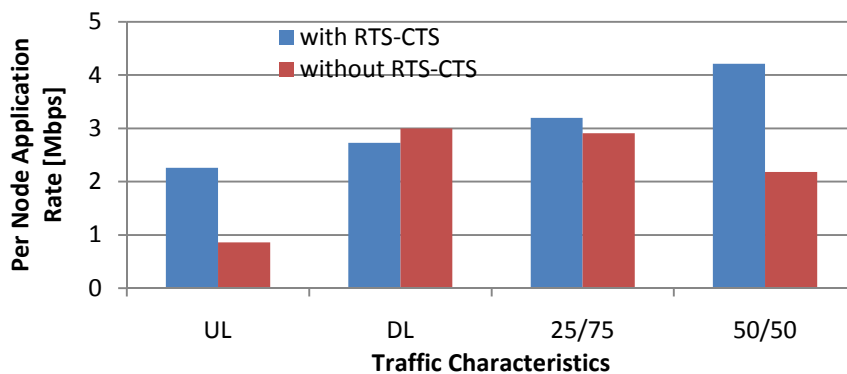


Figure 4.21 - Access Schemes Comparison in 2 Rings Scenario.

When the 100%DL case is considered the access scheme without RTS-CTS is achieving $R_{app} = 3.24\text{Mbps}$, while RTS-CTS $R_{app} = 2.72\text{Mbps}$. The theoretical maximum for CSMA/CA is

$R_{t_app}=3.33\text{Mbps}$ while for CSMA/CA with RTS-CTS it is 2.72Mbps . For CSMA/CA 97.2% of theoretical maximum is reached and for CSMA/CA with RTS-CTS the 100% is achieved. This is happening as each of the nodes receives on orthogonal channel, so the parent node sends each time the packets on non overlapping channels. It prevents from interferences so the maximum of radio interface capacity can be reached. In this case the limitation factor is capacity of dynamic radio interface of gateway node, as from this node all of the packets are being transmitted. For DL case it is not needed to use the RTS-CTS mechanism.

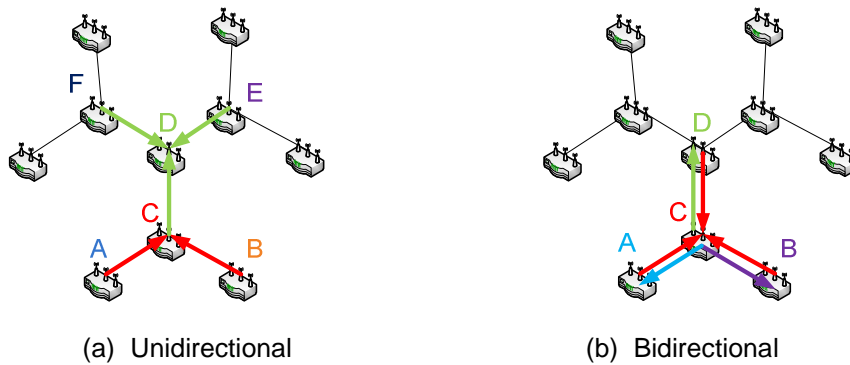


Figure 4.22 - Illustration of unidirectional vs. bidirectional traffic cases.

When the bidirectional traffic cases (25/75 and 50/50) are considered the RTS-CTS is beneficial once more. This is because of the same reason as in 100%UL case. As the flows are in both directions-uplink and downlink the same explanation as for uplink case is valid. Moreover bidirectional issue is arising, for example node from 1st ring receives from a parent and child nodes on one static interface channel as presented on the Figure 4.22(b). The transmission from Node D to Node C is parent->child transmission and from Node B to Node C is child->parent transmission. Node D is not aware of node B transmission and vice versa. Again this is the hidden node case for which RTS-CTS was originally developed. RTS-CTS mechanism is presenting its benefits by scheduling the transmissions.

As it can be seen on Figure 4.21 the more UL traffic proportion in the network is the more beneficial RTS-CTS becomes in case of bidirectional scenarios. For 25/75 traffic characteristics the R_{app} achieved per node is 3.20Mbps for RTS-CTS and 2.91Mbps for CSMA/CA. For 50/50 case, where all of the interfaces are loaded to the maximum the RTS-CTS application data rate is 4.21Mbps and CSMA/CA achieves 2.18Mbps . This again proves that when node is receiving simultaneous transmission from more than one node it is beneficial to use coordinated RTS-CTS access scheme. Based on this in all of following scenarios RTS-CTS handshake mechanism is used.

4.3.3 $K_{\text{Neighbourhood}}$

2 rings

For a 2 ring scenario the $K_{\text{Neighbourhood}}$ parameter study is conducted. The traffic in first case is unidirectional. In the second case discussed here the traffic is bidirectional. This ensures full usage of

all interfaces i.e. static and dynamic ones so that interferences are maximal. This is done to better understand the influence of $k_neighbourhood$ parameter. WLU usage function is used as the bidirectional traffic is simulated. Two output parameters are evaluated in this study: application data rate and convergence time. The trend equations and correlations are presented in the Table 4.16.

Number of channels is set to 4 as the studies of ring scenario show that with this number of channels the network in 2 rings topology can already come close to the R_{t_app} . Moreover, using this number of channels should present maximum influence on the τ_{conv} , while taking larger N_{ch} shall be of lower influence. Taking as an example $N_{ch} = 11$ the R_{app} will be maximum as all of the nodes will be able to assign to static interface the channel that is not used by any other node in the network. Moreover after first channel assignment there will be no change as any of the nodes will easily assign not reused channel. That will result in low convergence time in 2 ring scenario.

If lower N_{ch} is considered however the channel assignment at one node may influence other nodes choice as this particular assigned channel by node M_a can be reused 2 hops away by node M_b . This influence the next choice of static channel of node M_b . If this node changes channel it may influence the M_c channel change decision which can be situated in interference range of first node M_a . In this way the τ_{conv} grows.

In 2 rings scenario gateway is aware of all the channel assignments as it is central point and even for $k_neighbourhood=2$ it knows about all the channel assignments in the network. The difference is visible for 1st and 2nd ring nodes. For example the 2nd ring node is taken into consideration. This node knows and reacts for a change of static channel of 3 other nodes only for $K_neighbourhood=2$ as in Figure 4.23. For $k_neighbourhood=3$, it is aware of 5 other nodes and for $k_neighbourhood=4$ it is aware of every other nodes static channel assignment. This results in overall better assignment leading to higher application data rates per node, but at the cost of the higher convergence time of the network.

Let the 2nd ring node marked on Figure 4.23. The $K_neighbourhood$ areas are presented there. For the $K_Neighbourhood$ of 2 the area that the node is aware of channel assignment consists of 4 nodes. There are 4 orthogonal channels to assign. Since it is WLU function the channel used by gateway will not be assigned to other nodes the RCA will make sure that each of the node in the marked area has got different channel assigned. The same will be happening in all of the areas that consist of 4 nodes interconnected.

The same node, but using the $k_neighbourhood= 3$ will consider 6 nodes while choosing its static channel. Again the gateway channel will be protected, the 1st ring nodes channels` will be rated higher than those used by the other last mile node, not circled. This will result in assigning to the node circled the same channel. The same situation shall happen for other 2nd ring nodes.

When the $k_neighbourhood$ will be changed to 4, each node will be aware of channel assignment of every other node. This will result in distribution of channels according to weights, what will result in gradual increase of Channel Usage, meaning each channel shall be used by increasing number of nodes.

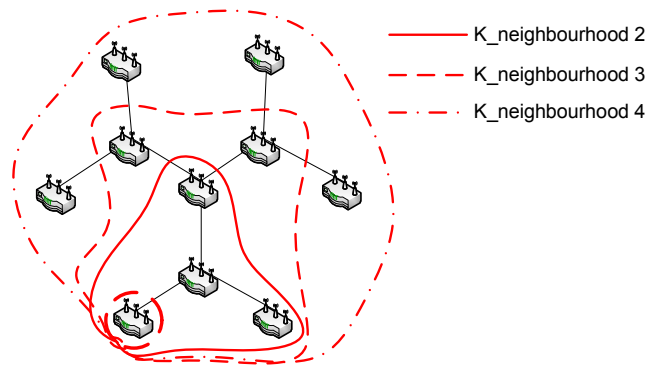


Figure 4.23 - The area of K_Neighbourhood

The examples of channel assignments for $k_neighbourhood = 2$, 3 and 4 are presented on the Figure 4.24. The Channel Usage for studied scenarios is presented in the Table 4.14. As WLU is used and $N_{ch}=4$ the gateway channel will be reused in all of the scenarios only once. As one can observe the most equal of channel usage is the one for $k_neighbourhood = 2$, than for $k_neighbourhood = 3$ and the most unequal distribution i.e. one channel is reused 6 times, is for $k_neighbourhood = 4$.

On the Figure 4.25 the impact of $k_neighbourhood$ parameter on application data rate is shown. For the bidirectional traffic case the higher the $k_neighbourhood$ size is the better performance network is presenting. In the unidirectional scenario the $k_neighbourhood$ parameter increase is decreasing the achieved Application Data Rate by each node. The percentage of theoretical application data rate is presented in the Table 4.15 at the end of the section.

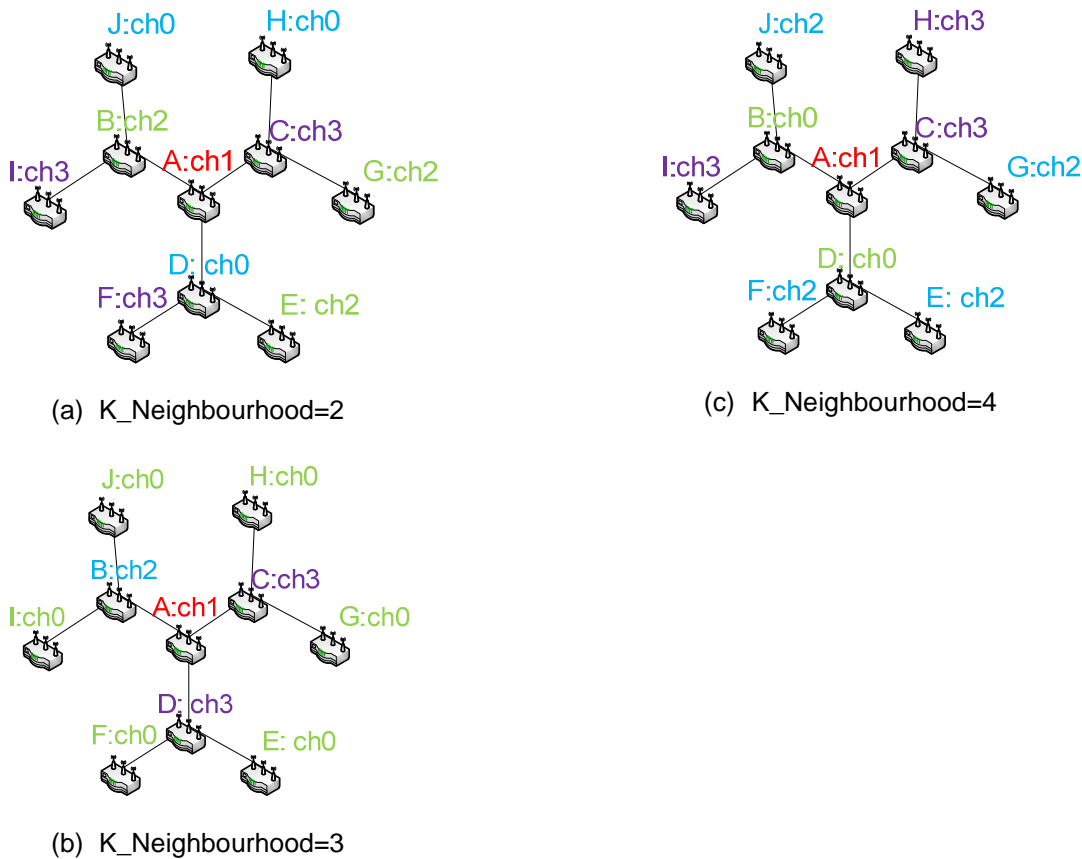


Figure 4.24 - Example channel assignment in 2 Ring Scenario for WLU.

Table 4.14 - Channel Usage in K_Neighbourhood Study.

Channel Number	K_Neighbourhood		
	2	3	4
0	3	6	2
1	1 (GW)	1 (GW)	1 (GW)
2	3	1	3
3	3	2	4

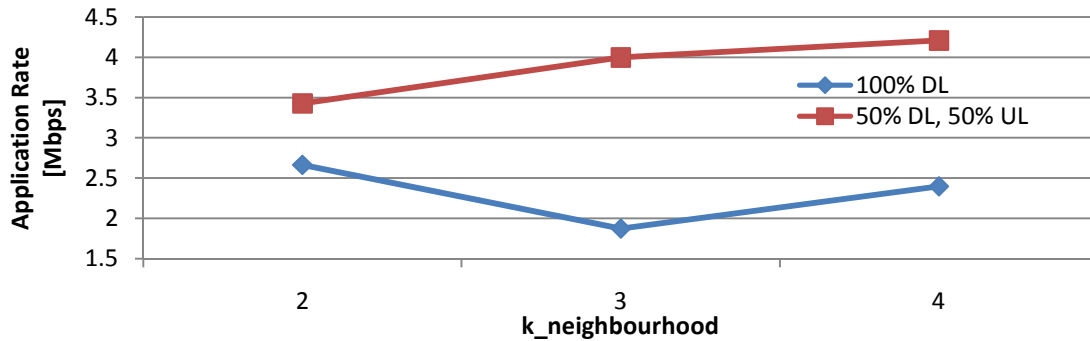


Figure 4.25 - Application Data Rates for various K_Neighbourhood

Table 4.15 - Percentage of Theoretical Maximum achieved In K_Neighbourhood study in 3 rings scenario.

		$R_{t_app}[\%]$		
		$K_Neighbourhood$		
	$R_{t_app}[\text{Mbps}]$	2	3	4
DL	2.72	98.0	68.9	88.2
50/50	5.44	63.0	73.5	77.4

As clearly seen on the Figure 4.25 this has got influence on application data rate achieved for DL traffic case. The higher the $k_neighbourhood$ the performance is worse in general. This is peculiar for DL case. For example 1st ring nodes- B,C,D are transmitting only to 2nd ring nodes, which means that in $K_neighbourhood=3$ they are transmitting only to nodes using the same channel Ch0 which causes high interferences. For the cases of $k_neighbourhood=4$ there are 2 channels utilised by 2nd ring nodes, which makes the interferences lower than in former case but larger than in $k_neighbourhood=1$ where 3rd ring nodes utilise 3 channels.

When the traffic characteristic changes to bidirectional traffic the influence of $k_neighbourhood$ study is opposite. The higher the parameter is the better the performance becomes. This means that for uplink case the WLU channel assignment is very beneficial. As for WLU the channels are rated according to their importance (distance from the gateway) the less used channels are assigned to more important nodes with the gateway being the most important. This is the reason why WLU has

been developed. As with the *neighbourhood* increase more nodes know which channels are important and which are not, the closer to ideal WLU assignment is made. In UL traffic part of bidirectional traffic the 2nd ring nodes are not receiving any packets the fact that all of 6 nodes are using this channel does not introduce any interference.

Average convergence times are presented on Figure 4.26. As one can see the higher $K_{neighbourhood}$ the longer it takes the network to converge. This happens as for higher $K_{neighbourhood}$ each node possesses the knowledge about larger part of the channel assignments in the network, and has to react for the change of nodes further away. This has been explained before.



Figure 4.26 - Convergence Times for various K_Neighbourhood

The convergence time of the network is connected with the T_{hello} packet time interval. In all of the scenarios the T_{hello} packet interval is fixed to 3s. Nodes gather the information of other nodes static interface channel change, perform their static interface channel change and broadcast the T_{hello} packet. This is why, the higher $K_{Neighbourhood}$ parameter is the more time it takes other nodes to be notified about the change. If the node is 4 hops away it may even take up to $4 \times T_{Hello}$ interval in the worst case. Each node change its static channel not once so the more nodes there are to consider the longer convergence time is.

The delay results are presented on the Figure 4.27. Those are proportional to the achieved application data rates from Table 4.15. This is happening as the lower the application data rate is the more bandwidth the nodes have in disposal so that the packets are being transmitted faster. The trend equations and correlations are presented in the Table 4.16.

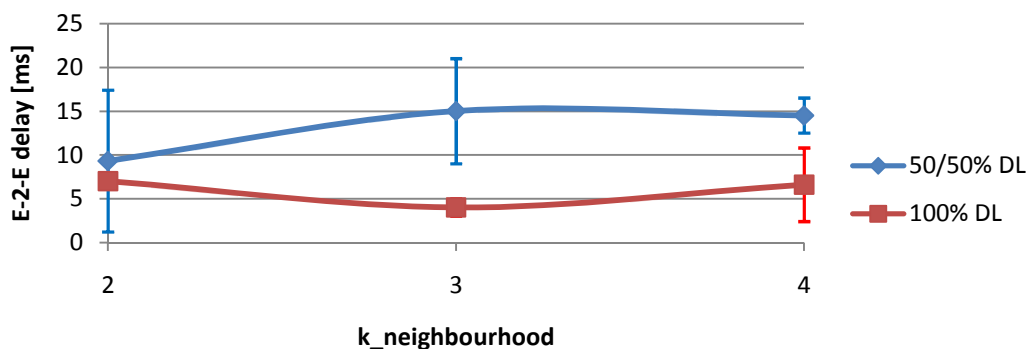


Figure 4.27 - E-2-E delay for various K_Neighbourhood.

Table 4.16 - Equations and Correlations for K_Neighbourhood study, 2 Rings.

K-Neighbourhood (K_N) vs.:	Equation	R ²
R_{app} , 100%DL, 2 Rings	$R_{app} = 0.658 \times K_N^2 - 2.766 \times K_N + 4.775$	1
R_{app} , 50/50, 2 Rings	$R_{app} = -0.180 \times K_N^2 + 1.112 \times K_N + 2.496$	1
τ_{conv} , 2 Rings	$\tau_{conv} = 1.1 \times K_N^2 + 4.9 \times K_N - 9.4$	1
τ_{max} , 2 Rings 50%/50%	$\tau_{max} = -3.1 \times K_N^2 + 21.2 \times K_N - 20.7$	1
τ_{max} , 2 Rings 100% DL	$\tau_{max} = 2.8 \times K_N^2 - 17 \times K_N + 29.8$	1

3 rings

For a 3 ring scenario the influence of $k_{neighbourhood}$ is also studied. At this point the number of available channels is set $N_{ch} = 11$ as there are 19 nodes to assign the channels to.

Application Data Rates achieved by each node in the network, in 3 rings scenario, are presented on Figure 4.28 while their performance compared to theoretical maximum in Table 4.17. For both traffic characteristics the application data rate for each node increases. As clearly visible the higher the $K_{neighbourhood}$ parameter is the higher the achieved application data rate. For 19 nodes, 11 available channels and interference range covering each node it is beneficial to be aware of channel assignment of larger part of the network. As WLU is used, the nodes further away from the gateway are assigned channels more frequently as they are not so important as gateways or 1st ring node. Having $k_{neighbourhood}=4$ helps to achieve that.

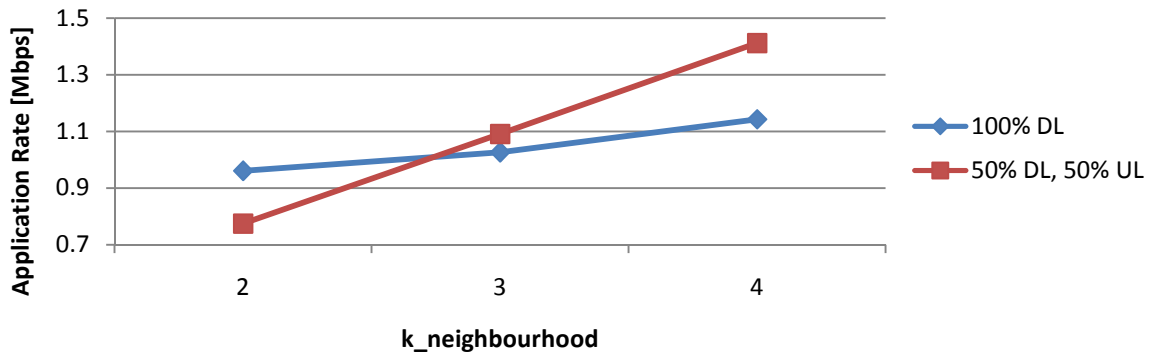


Figure 4.28 - Application Data Rates for 3 Ring scenario.

Table 4.17 - Percentage of Theoretical Application Data Rate achieved in 3 Ring Scenario.

		$R_{t_app}[\%]$		
		K_Neighbourhood		
	$R_{t_app}[\text{Mbps}]$	2	3	4
DL	1.360556	70.6	75.4	84.0
50/50	2.721111	28.5	40.1	51.9

Comparing application data rates for both traffic characteristics one can observe that for 50/50 traffic the achieved results are not better than for unidirectional traffic results, while in 2 rings scenario it is present. This is happening as in 2 ring scenario the number of nodes transmitting in both directions, UL and DL, is 4 nodes out of 10. In 3 ring scenario however those nodes are in number of 12 out of 19. Relatively it is more, what leads to more heavy usage of resources, not allowing to achieve higher application data rates than for unidirectional.

Example channel assignments are presented on Figure 4.29 for $K_{neighbourhood} = 2, 3$ and 4 respectively. The channel usage is presented in Table 4.18. As in 2 rings scenario in the $K_{neighbourhood}$ case the channel distribution is most equal, as the nodes know the largest areas of network. This leads to better performance of the network, presented in Figure 4.28.

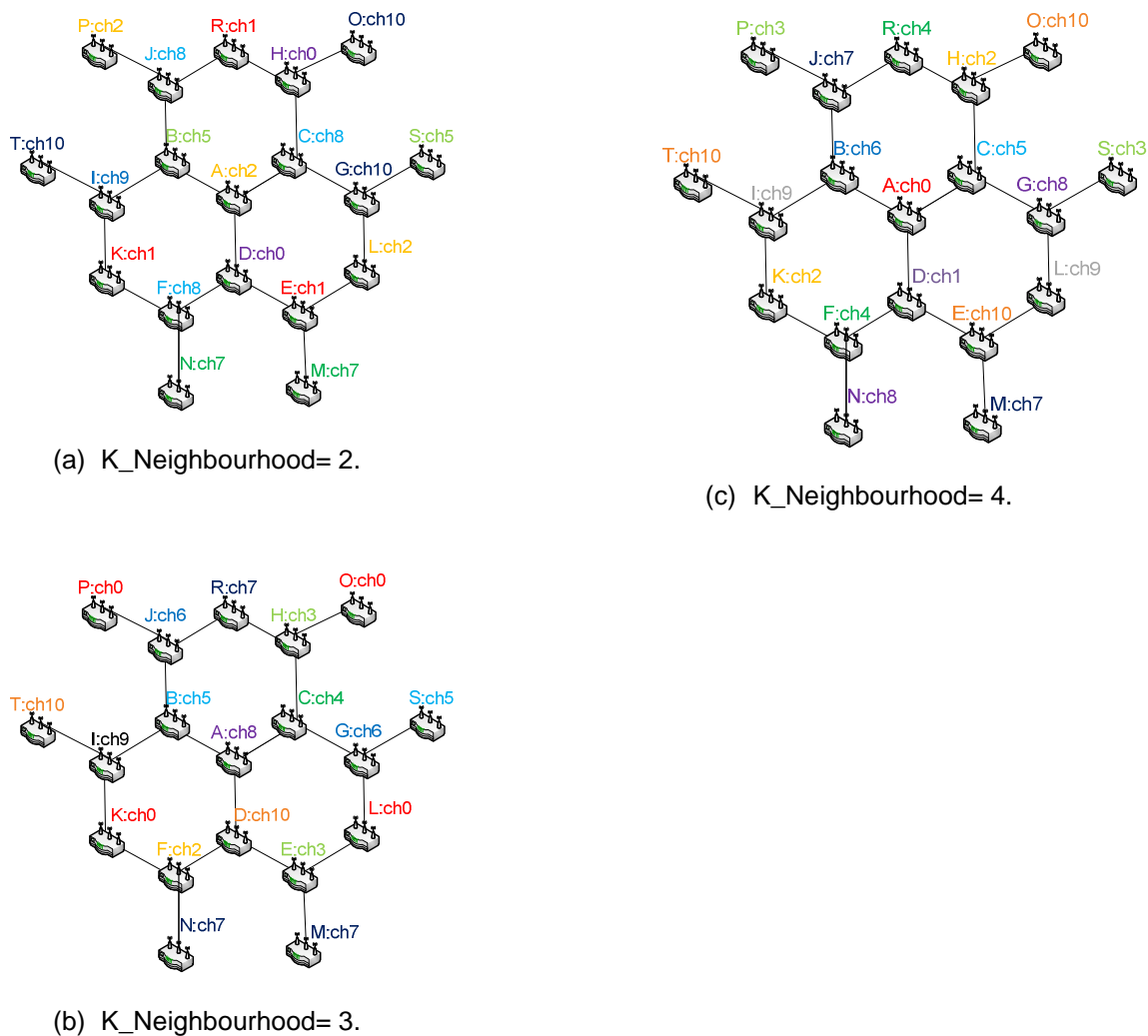


Figure 4.29 - Example Channel Assignment in 3 Ring Scenario for WLU.

The $K_{neighbourhood}=2$ is the worst case as nodes, knowing only about channel assignment of their 3 One-Hop neighbours assign randomly the channel from 8 remaining ones. As it presented in Table 4.18, 3 of the channels are not exploited at all by any of nodes. This forces other nodes to utilize the same channels as other ones in their interference area. That causes collisions and decreases the performance. Moreover the channels which is supposed to be protected the most i.e. gateway channel

is reused 3 times in the network, by 3rd ring nodes (Node P and L), because gateway is not in their $K_neighbourhood$ area. Other nodes i.e. node J, G and E are transmitting on the channel Ch2 causing interferences at a gateway node

Situation improves with increase of $K_Neighbourhood$ to 3. As all the nodes are now aware of the gateway's static channel assignment, none of nodes is fixed on the same channel. It leads to performance increase by 12% of R_{t_app} . What is more only one channel is not being utilised in the network, so the radio resources are used more efficient.

The best performance is observed when $K_Neighbourhood$ is 4. All of the channels are utilised, channels of important nodes (GW, 1st ring nodes: Node B, C and D) are not used by any other nodes in the network so that the interferences received by important nodes are kept at the lowest level.

As one can observe from the Figure 4.30, the average convergence time in the 3 rings scenario also increases together with the $k_neighbourhood$ parameter increase. This time 11 channels available is relatively more than 4 channels available to 10 nodes. That is why, in 3 ring scenario, for $k_neighbourhood=2$ the convergence time is higher than for 2 ring scenario. As the network is larger and the $k_neighbourhood$ area smaller each time more packets must be transmitted to fully converge the network. Each time the channel change influences only nodes 2 hops further, so to converge the network it will take more time than for $k_neighbourhood=3$ or 4, where each time the hello packet influences larger part of the network than for $K_neighbourhood=2$. This results in shorter convergence time than in 2 ring scenario. The trend equations and correlations are presented in the Table 4.19.

Table 4.18 - Channel Usage in 3 Rings Scenario.

Channel	K_Neighbourhood		
	2	3	4
0	2	4	1 (GW)
1	3	0	1
2	3 (GW)	1	2
3	0	2	2
4	0	1	2
5	2	2	1
6	0	2	1
7	2	3	2
8	3	1 (GW)	2
9	1	1	2
10	3	2	3

In the scenario there are no nodes switching on or off during the simulation so the channel assignment is steady. In realistic scenarios however, some nodes may be switched off while other may appear after being switched on. In this case the higher the $K_neighbourhood$ parameter is the less stable and more fragile to changes the network is. Depending on the type of the network the $K_neighbourhood$

parameter must be set to balance between stability and performance.

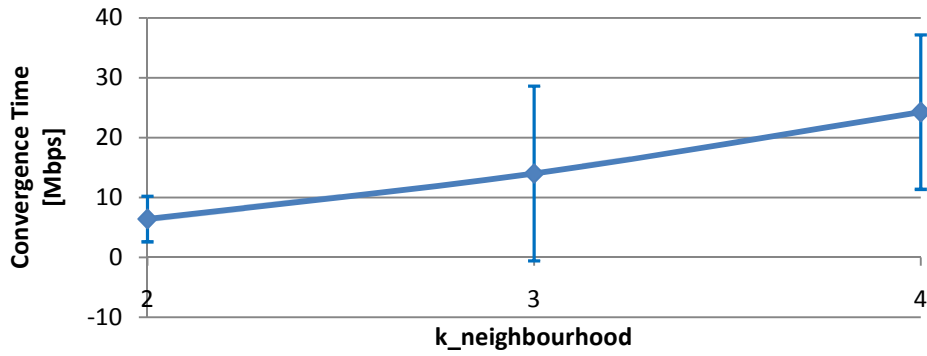


Figure 4.30 - Convergence Times for Various K_Neighbourhood.

The delays obtained in 3 ring study are presented on the Figure 4.31. In the DL case the delays are higher as relatively the congestion is higher as showed in Table 4.17., than in bidirectional traffic case. The 50%/50% traffic case is achieving lower delays as less traffic is forwarded and this creates resources for faster multihop transmission.

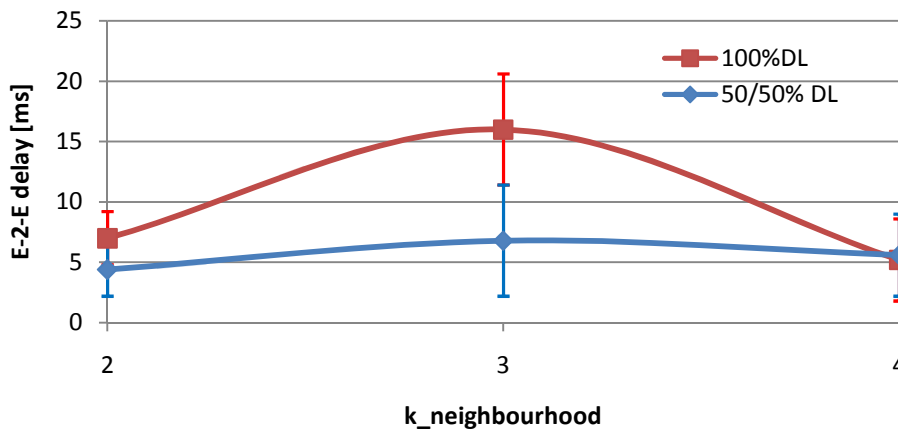


Figure 4.31 - E-2-E delays for K_Neighbourhood.

Table 4.19 - Trend Equations and Correlations for K_Neighbourhood study, 3 Rings.

K-Neighbourhood (K_N) vs.:	Equation	R ²
R_{app} , 100%DL, 3 Rings	$R_{app} = 0.025 \times K_N^2 - 0.011 \times K_N + 0.945$	1
R_{app} , 50/50, 3 Rings	$R_{app} = 0.002 \times K_N^2 + 0.310 \times K_N + 0.461$	1
τ_{conv} , 3 Rings	$\tau_{conv} = 1.325 \times K_N^2 + 0.975 \times K_N - 0.85$	1
τ_{max} , 3 Rings 100% DL	$\tau_{conv} = -9.9 \times K_N^2 + 58.5 \times K_N - 70.4$	1
τ_{max} , 3 Rings 50%/50%	$\tau_{conv} = -1.8 \times K_N^2 + 11.4 \times K_N - 11.2$	1

4.3.4 Number of channels and usage function for DL only

As it has been checked before the $k_{neighbourhood}=4$ is performing better for ring topologies, thus it was chosen for channel number study. For cases of 2 and 3 ring scenarios the channel number is being increased. Both Usage Functions are evaluated. The transmission power is set to 200mW. The

results from 2 ring scenario study are presented in Annex D.

Results from 3 rings, $k_{neighbourhood}=4$ study are presented in the Table 4.20 and on Figure 4.32. For 3 rings scenario the $R_{t_app} = 1.36Mbps$ which is not achieved in the study. Single radio nodes are achieving performance of 8.8% of theoretical maximum, which equals to 0.12Mbps.

Table 4.20 - Relative to Theoretical, Application Data Rate for 3 Ring Scenario.

		R_{t_app} [%]		
Single Radio		8.8		
Multi Radio N_{ch_ort}		4	7	11
UF	LU	40	46	80
	WLU	22	55	84

Nodes set to utilise 4 orthogonal channels achieve application data rates per node 0.54Mbps and 0.3Mbps for LU and WLU UF respectively. It is 40% and 22% of theoretical maximum. The lower performance of WLU is because the gateways Ch1 channel is reused only once in the whole 19nodes network. The remaining 3 channels are not able to achieve the same performance as 4 channels reused by all the nodes in LU 4channels scenario. The distribution of channels is presented on Figure 4.33 for WLU and LU UFs. Moreover numbers of nodes using particular channel in the network are presented in the Figure 4.33. As one can observe the channels used by gateway and nodes from 1st ring are reused the least times in the whole network. This is because weights assigned to those channel while evaluating the channel usage by each node are the highest, reducing number of nodes that use those channels. Comparing it to LU channel usage statistics one observe equal distribution of channels. In LU function only the number of nodes using each particular channel is evaluated, so the result is alike distribution of the channels.

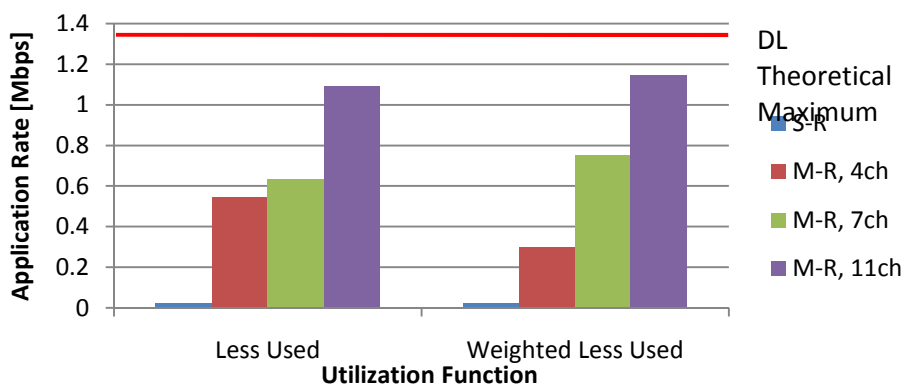


Figure 4.32 - Per Node Application Data Rate for 3 Rings Scenario.

Results from 7channels study present that LU UF allows each node to be provided with R_{app} at the level of 46% of R_{t_app} , while WLU utilization function is allowing $R_{app_max} = 55%$ of R_{T_app} . This number of channels is not enough to use the WLU capabilities. However it is already better performing than LU UF channel assignment. The channel assignment is presented on Figure 4.34 for both UFs.

The Number of nodes using each channel is presented in the Table 4.21.

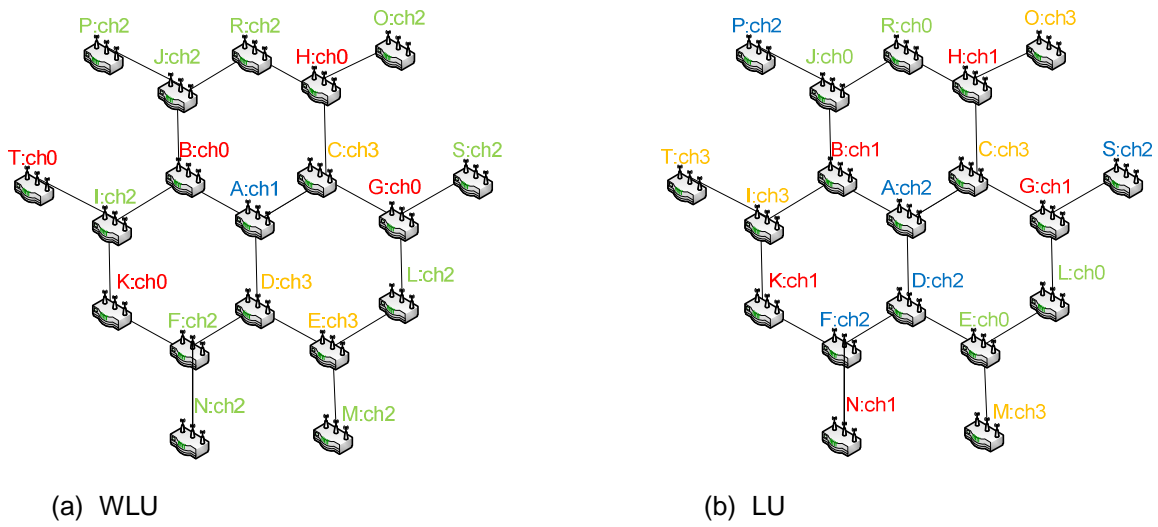


Figure 4.33 - Radio Channel Assignment For 3 Rings, 4 channels.

Table 4.21 - Channel Usage Statistics for 3 Rings Scenario: 4 channels.

UF	WLU	LU
Ch. No.	N_n	N_n
0	5	4
1	1	5
2	10	5
3	3	5

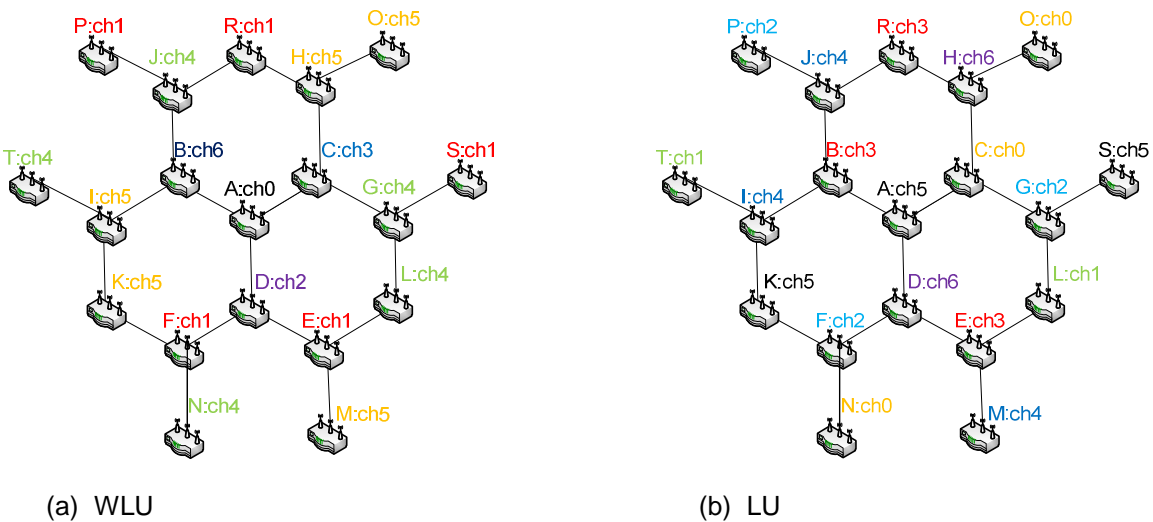


Figure 4.34 - Channel Assignment in 3 Ring Scenario 7channel.

As one can observe when WLU is used the channel used by gateway and 3 nodes of 1st ring (Node B,

C, D) are not reused by any other nodes in the network. This is advantageous compared to LU UF as other nodes than the ones mentioned are using the same static channel, causing interferences. For example Node J when transmits to Node R, does it via channel Ch3. The same channel is used by a Node B to receive from Node A. In this case Node B receives RTS packet sent by J to R, sets the NAV vector and defers from receiving.

Worse situation happens when Node D is considered. It receives on channel Ch6 from Node A. On the same channel Node H is receiving from Node C. As both nodes A and node C have got different static channel set they will not receive RTS nor CTS messages of the transmission between A-D and C-H. This will make both nodes transmit simultaneously causing collisions, because Node H is in interference range of Node A and Node D is in interference range of Node C.

In study where 11 channels are used both Utilization Functions are performing well, allowing satisfactory usage of radio resources and achieving the 84% R_{t_app} by a WLU, while LU 80%. As no more channels are available to use in 802.11a this is the maximum value of application data rate that can be reached in 3 rings, 100%DL scenario. The Figure 4.35 presents the channel assignment for WLU and LU usage functions. In the Table 4.23 the corresponding statistics of channel usage are presented.

The same as in 7channels study one can see that WLU assign the gateway and 1st ring nodes the channels that are not used by any other node in the network. Moreover the assignment of channels to 2nd ring nodes (E, F, G, H, I and J) is also orthogonal. Each of them has got other channel assigned. What is more the channels used by 2nd ring nodes are reused in minimal distance of 4 hops. For example the channel used the most Ch3 is reused by Nodes G, N and P which all are 4 or 5 hops away from each other. This assignment assures that the interferences are kept lowest possible.

Table 4.22 - Channel Usage Statistics for WLU: 7 channels.

UF	Ch No.	0	1	2	3	4	5	6
WLU	N_n	1	5	1	1	5	5	1
LU	N_n	3	2	3	3	3	3	2

Analysing LU usage function shows that the channel assignment is also limiting the interferences. However in some configurations the collision may occur. The example can be Node O and Node I, receiving on channel Ch8. As the Node B is in the interference range of Node H, some of the packets may be corrupted. This however is not of a high probability that is why the difference between R_{app} achieved by WLU and LU is only 4% of R_{t_app} .

The benefit of using WLU channel distribution is not high as unidirectional traffic is considered. RCA do not take into account the distribution of channels between neighbouring nodes, which are not directly connected with each other, for example nodes from 4th ring. If those nodes have the same static channel assigned the nodes from ring before that are transmitting to them will cause the collisions between each other.

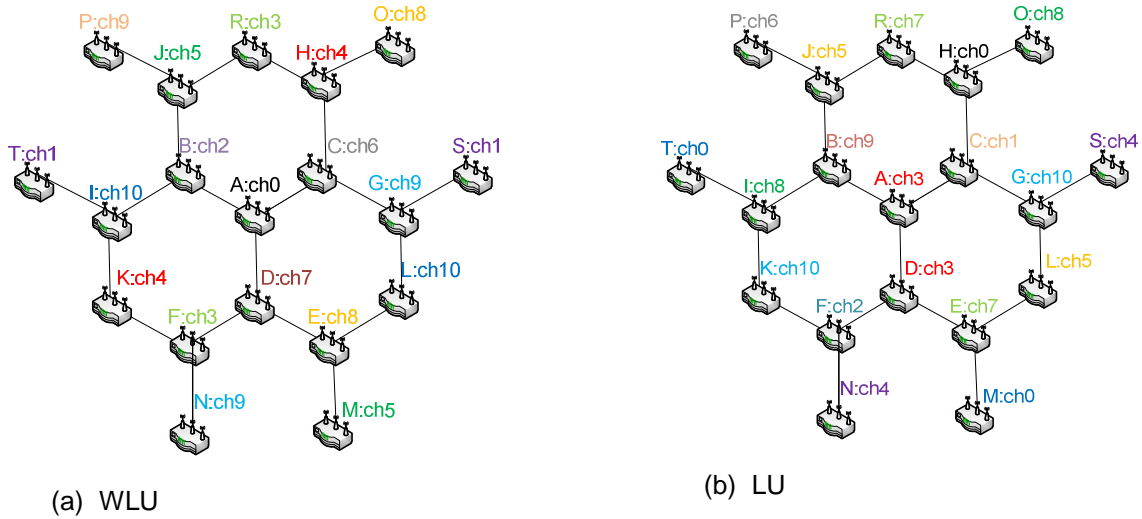


Figure 4.35 - Channel Assignment in 3 Ring Scenario: 11channel

Table 4.23 - Channel Usage Statistics in 3 Ring Scenario: 11 channels.

UF	Ch No.	0	1	2	3	4	5	6	7	8	9	10
WLU	N_n	1	2	1	2	2	2	1	1	2	3	2
LU	N_n	3	1	1	2	2	2	1	2	2	1	2

PER from 3 rings study is presented on Figure 4.36. It corresponds to the application data rates achieved by various configurations presented on Figure 4.32. For the 4 channels the performance, in terms of achieved R_{app} , the LU UF is better than WLU. It is able to transmit more packets, but also cause more collisions. This is valid for 7 and 11 channels cases as well.

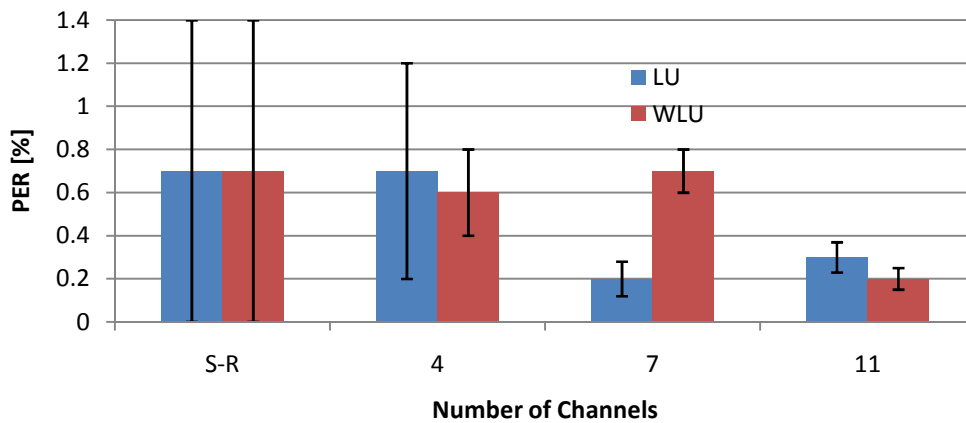


Figure 4.36 - PER in 3 Rings Scenario.

Delay study, showed on the Figure 4.37, also confirms above statement. As the configuration, presents better performance in terms of R_{app} the delay is higher than for other UF. This is because the more packets there are to be sent the more other ones need to wait until the interface is ready to transmit it. The trend equations and correlations are presented in the Table 4.24.

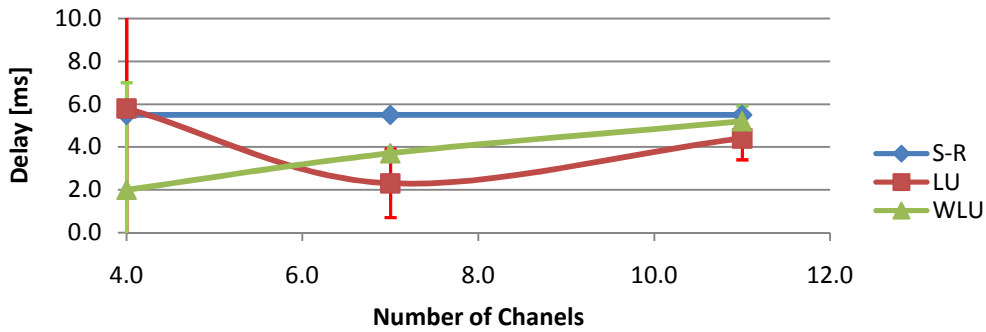


Figure 4.37 - Delay in 3 Rings Scenario.

Table 4.24 - Trend Equations and Correlations for Channel Number Study, 3Rings, DL.

Number of Channels (N_{ch_ort}) vs:	Equation	R^2
τ_{max} : WLU	$\tau_{max} = 0.241 \times N_{ch_ort}^2 - 3.825 \times N_{ch_ort} + 17.23$	1
τ_{max} : LU	$\tau_{max} = -0.027 \times N_{ch_ort}^2 + 0.867 \times N_{ch_ort} - 1.033$	1
τ_{max} : S-R	$\tau_{max}=6.4$	1

4.3.5 Number of channels and usage function for UL only

For the UL study of number of channels the same scenarios (2 and 3rings) with the same configurations were used for analysis.. The only difference is that the traffic originates from the nodes in the network and goes to the central, Gateway node. The results from 2 Ring studies are presented in Annex D.

Results from 3 rings, channel number UL study are presented on the Figure 4.38 and the relative to theoretical maximum values are in Table 4.25. The results present analogical situation to the 2 ring scenario.

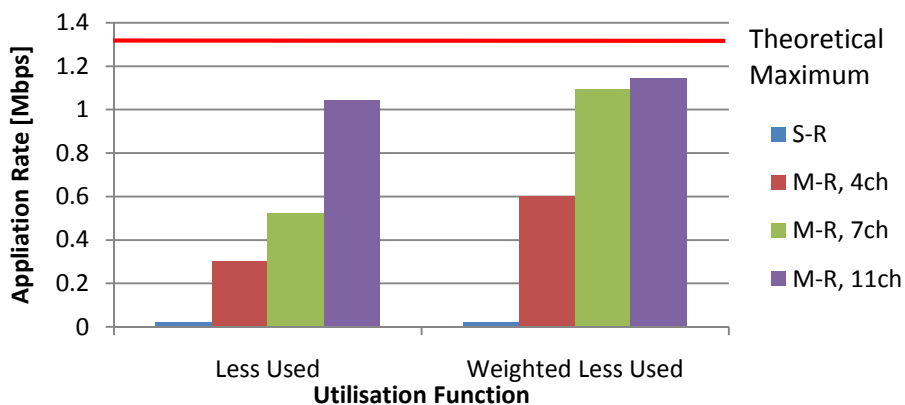


Figure 4.38 - Channel Number Study for 3 Ring Scenario UL.

The first analysed case of $N_{ch_ort}=4$ presents poor performance as not many channels are possible to be reused. The WLU is 2 times better as the gateway channel is used only once in the network and in WLU case it is used 5 times, causing high packet loss. The channel assignment is on Figure 4.33. This is analogical to $N_{ch_ort}=2$ and 3 from previous, 2 rings study.

The next analysed value of $N_{ch_ort}=7$ presents high disproportions between LU and WLU as well. This time WLU forward more than 2 times the traffic that LU manages to forward. This again has to do with the strategy of protecting the channels used by gateway and nodes close to it, as on Figure 4.34.

The maximum value of 11 channels to utilise by the network presents similar performance, with the difference of 7%. It is not possible to utilise more channels by the system in use so the WLU 11channels 84% is the maximum performance the network can achieve. One can deduct that as the WLU and LU performance is similar further increase of channels will not result in application data rates closer to theoretical maximum. This as in previous case is connected with the inability of nodes to successfully conduct RTS-CTS handshake on orthogonal channels.

Table 4.25 - Relative to Theoretical, Application Data Rate for Various Channel Number.

	R_{t_app} [%]		
single radio	1.5		
Multi Radio N_{ch_ort}	4	7	11
LU	22	38	77
WLU	44	80	84

The delays from 3 ring study are presented on the Figure 4.39. As one can observe from the curves the scenario that is mostly congested is the WLU 11 channels where the delays are maximal. With the increase of the channels the delays increase as well, while the R_{app} is being kept at the similar level so the network has reached the congestion and the maximum of performance in terms of application data rate. Further increase of channels would result only in delay decrease but not in the application data rate increase. The trend equations and correlations are presented in the Table 4.26. The case of 7 channels it is clearly seen that using WLU is highly beneficial in terms of radio resources savings.

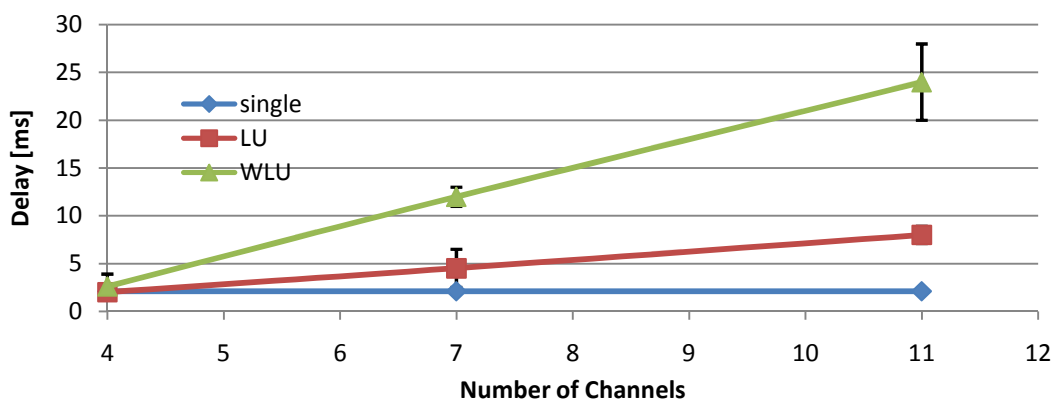


Figure 4.39 - Delay For Channel Number Study in 3 Rings Scenario UL.

Table 4.26 - Trend Equations and Correlations for Channel Number Study, 3Rings, UL.

Number of Channels (N_{ch_ort}) vs:	Equation	R^2
τ_{max} : WLU	$\tau_{max} = 3.054 \times N_{ch_ort} - 9.529$	0.999
τ_{max} : LU	$\tau_{max} = 0.858 \times N_{ch_ort} - 1.459$	0.999
τ_{max} : S-R	$\tau_{max}=2.1$	1

4.3.6 Traffic direction

Next study is to analyse what is the network performance depending on direction of traffic generated. There are four cases to be studied, which are varying $r_{t_gen}=0/100$ which is 100% downlink traffic, $r_{t_gen}=100/0$ which is 100% uplink traffic, $r_{t_gen}=50/50$ which equal 50%DL and 50%UL and $r_{t_gen}=25/75$ that is 25% UL to 75% DL traffic. The WLU UF is used as at this point the gateway stable channel will be used for receiving and it is beneficial to protect the channel used by it, which is most important channel in the network as it gathers all the traffic from the network. Maximum number of $N_{ch_ort}=11$ is used as to allow maximum network capacity and the network topology is 2 rings with 10 nodes.

The results from study are presented in the Figure 4.40. Theoretical maximum of R_{app} based on (3.7) is taken as reference. It is achieved when only the downlink is analysed as for the 10 nodes scenario using 11 channels each node is assigned orthogonal channel. The capacity imitating factors are physical capacities of dynamic (for DL) and static (for UL) interfaces. For both unidirectional cases the capacity is summed. Two of the Usage Functions are analysed. The results are the same as 11channels used by 10 nodes results in the same performance no matter in what manner are the channels distributed, because each node gets other channel.

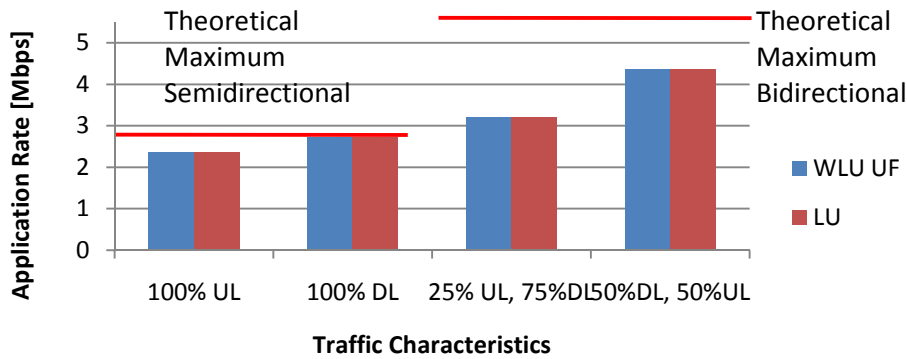


Figure 4.40 - Traffic Direction Study.

For unidirectional studies, 100% UL and 100%DL cases are considered. The R_{app} per node is 2.35Mbps for UL and 2.72Mbps for DL. It is 86.2% and 100% of R_{t_app} respectively. For that comparison however the values from One-Hop neighbour study must be taken into account. In fact for UL scenario the maximum cumulative application data rate that can be achieved by gateways interface is 21.55Mbps. When this is divided for 9 nodes that are active in Traffic Direction study 2.39Mbps per node. This is only 0.04Mbps difference, so one can say that results are expectable. Here again it is shown that RTS-CTS is not working in multichannel environment, as in Traffic Direction study each of 10nodes has got different static channel assigned. This is the reason why in UL the performance is lower than in DL.

When a traffic mix is considered the achieved R_{app} per node is higher than when unidirectional traffic is being considered. For a $r_{T_gen} = 25/75$ the value is 15% higher than when only downlink is

considered. The increase of received R_{app} is because two interfaces from each node are working simultaneously, doubling the available radio resources. As an example consideration let the gateway node be taken. Before it was only transmitting or only receiving from other nodes. In bidirectional traffic case when the dynamic interface transmits to one node, the static interface can be receiving from remaining two one-hop neighbours.

On the other hand the bidirectional traffic, creates two traffic flows, one UL and one DL, which need to be forwarded. If the chain from a ring scenario is separated as on Figure 4.41 one can see that compared to unidirectional traffic, in bidirectional traffic case the static radio must be used to receive from two nodes i.e. node B is receiving from C and A. What is more dynamic interface is used to transmit to 2 neighbouring nodes, opposing to the 1 node in unidirectional case. As one can see node C when transmitting to node B use the same channel by dynamic interface as node A dividing the resources of static radio of node B by 2 nodes. The same situation is present when node D transmits to C and node B transmits to C, where D and B use the same dynamic interface channel to communicate with node D. Because of interferences caused by it and the fact that static interface reception time is divided by two nodes and is not given to one node as in unidirectional scenarios the R_{app} in bidirectional traffic scenarios cannot reach the capacity of double the unidirectional traffic scenarios, which is $R_{2t_app}=5.44\text{Mbps}$. In last analysed case $r_{t_gen}=50/50$, the $R_{app}=4.2\text{Mbps}$, that is 77% of R_{2t_app} , which is the maximum R_{app} that user can get with UL and DL equal activity.

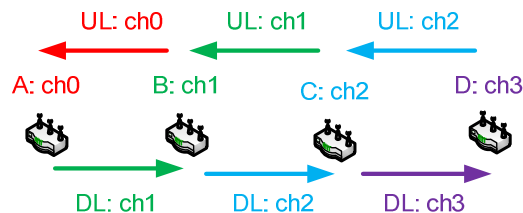


Figure 4.41 - Transmission channels between gateway and 1 active node over 3 hops.

The delays from the study are presented in the Figure 4.42. Although both usage functions are presenting the same performance in the achieved application data rate study, here the results are different. As the achieved application data rates are the same for each case for WLU and LU, the difference in delay shows that one UF is better than the other. For example as it has been showed in previous studies in UL traffic case the WLU performs better than LU. This is confirmed by lower delay in UL case.

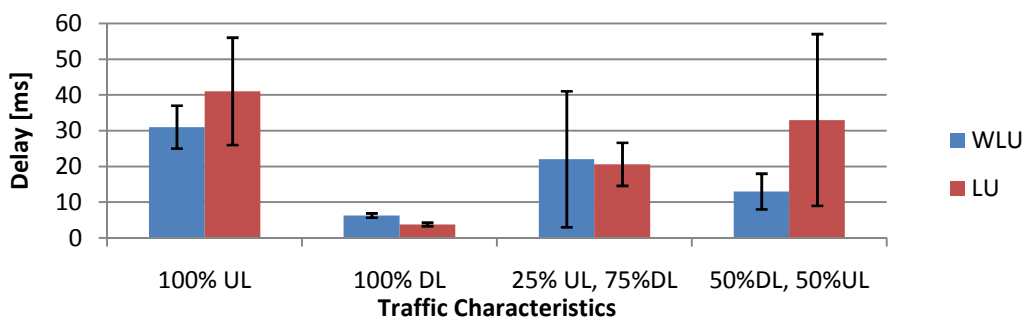


Figure 4.42 - Delays in 2 Rings Scenario for Traffic Characteristics Study.

3 rings

When a 3 ring scenario is considered the results become more varied. This is because there are fewer channels than nodes to assign the channels to. In those conditions the benefits of using WLU are showed. As it has been already studied in 4.3.5 section the WLU outperforms LU when the UL case is analysed. The same is visible on the Figure 4.43. Wherever the traffic heading to the gateway is present the WLU is achieving higher application data rate.

The theoretical maximum (2.7Mbps) for unidirectional (UL and DL) cases is not reached in any case as the OPNET interference range 1000m does not allow to have collisions free network. Moreover the UL case is limited by the described before RTS-CTS handshake problem.

In the bidirectional traffic case the performance of a network is similar to unidirectional one, while the theoretical maximum is 2x bigger than in unidirectional one. It can be observed in the Table 4.27 that the relative performance drops almost 2 times. This is because, as explained in 2 ring section, more transmissions are scheduled in bidirectional traffic case, resulting in higher interferences and more extensive usage of interfaces.

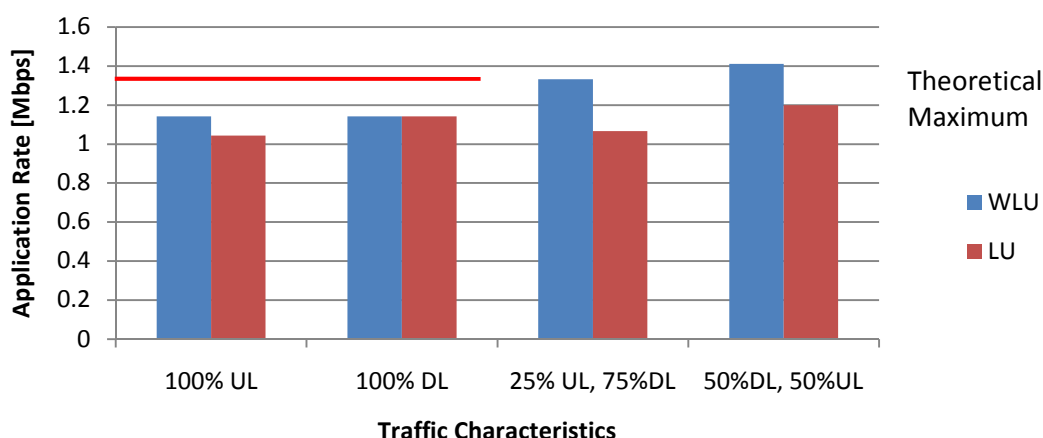


Figure 4.43 - Traffic Direction Study in 3 Ring Scenario.

Table 4.27 - Relative to Theoretical Application Data Rate Performance of WLU and LU UF.

	$R_{t_app}[\%]$			
	Traffic Characteristics			
	100%UL	100%DL	25%UL,75%DL	50%UL,50%DL
WLU	84	84	49	52
LU	77	84	39	44

In the Figure 4.44 the delays from 3 ring study are presented. As the traffic becomes equally distributed as in 50/50 case, the delays decrease, compared to 25/75 case. This is contradictory to what has been said that when the achieved application data rate increases the delays increase as well. Here the traffic is shifted from DL to UL, what results in optimal resources usage. Delays need to be analysed together with the achieved application data rate. When the R_{app} is higher, for example in

25/75 traffic, the delays will be relatively higher as well.

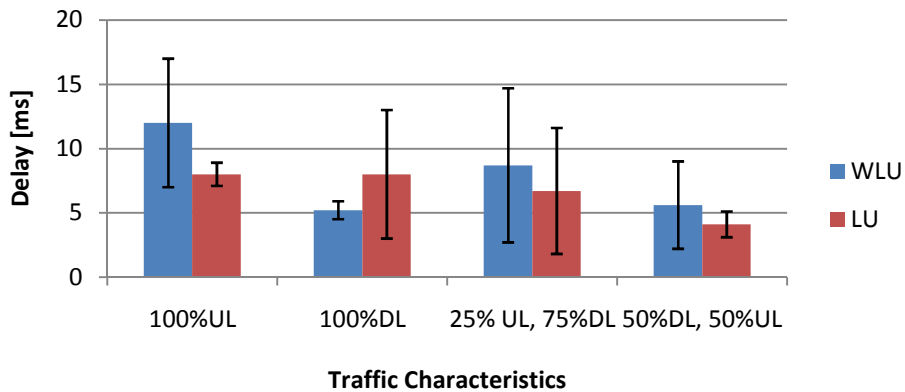


Figure 4.44 - Delays for Traffic Characteristics Study in 3 Rings Scenario.

4.3.7 Active nodes

The last study of hexagonal scenario is to analyse the network performance in the conditions of not every node transmitting. Fully congested network do not happen always. Usually some the nodes are transmitting simultaneously. In this scenario R_{app} per node is expected to be higher than in fully congested network studies. This is because as less number of interfaces is going to be used, less interference is present. Two scenarios are studied: 3 and 4 ring scenarios.

3 Rings

The number of active nodes $N_{n_{act}}$ is increased simulating the increase of network congestion. Nodes to transmit are picked up randomly. 3 rings scenario is taken for this study with WLU utilization function. This algorithm is expected to achieve better results in bidirectional traffic scenarios with $r_{t_{gen}}=25/75$ which means that each node's activity is 25% UL traffic and 75% DL traffic. Nodes are utilizing 11 channels as to allow achieving maximum R_{app} value not limited by the number of channels.

The nodes picked up to be active nodes are spread over the network to make the realistic scenario. Active nodes distribution and the active links are presented on following figures:

- Figure 4.45 (a) presents 1 random active node from 3rd ring,
- Figure 4.45 (b) shows 2 active nodes, where one is from 3rd ring and one from 2nd ring,
- Figure 4.45 (c) presents 4 active nodes where one node is from 3rd, two nodes from 2nd ring and one from 1st ring,
- Figure 4.45 (d) shows 7 active nodes where 2 nodes are from 3rd ring, 3 nodes from 2nd ring, and 2 nodes from 1st ring.

Results from study are presented in the Figure 4.46, trend equations and correlations are presented in the Table 4.29. One can see that for 18 nodes active the network achieve $R_{app} = 1.33$ Mbps which is the point where the saturation is reached for WLU, while for LU $R_{app} = 1.06$. The network starts to offer higher application data rates when the $N_{n_{act}}$ drops below 7, what equals around 40% of total

number of nodes. This happens as 7 or more active paths are generating the similar interferences as 18 active paths. Taking into consideration the transmission and interference ranges presented in the Figure 4.3 and applying them to Figure 4.45 utilizing random 7 paths makes almost all of the nodes transmitting. Some of the nodes are only being used as repeater, but still they are creating interferences. The less paths are active the less interferences are present, covering smaller area and allowing higher R_{app} .

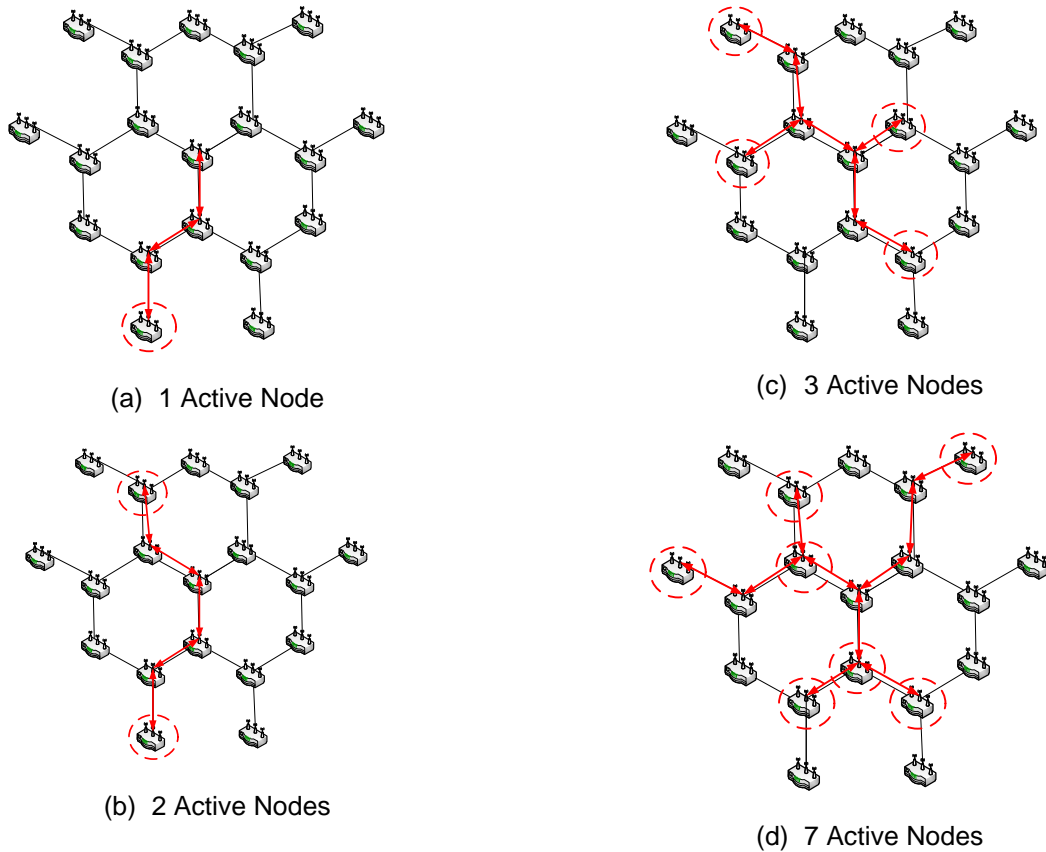


Figure 4.45 – Active Nodes in 3 Ring Scenario

In general the LU UF is performing worse. This is mainly because the traffic is party UL (25%) and as one recalls, from Figure 4.38 or Figure 4.43 the WLU is better than LU for UL traffic case. This is especially seen when the Number of Active nodes decrease as than only few paths are active, more traffic is sent and more collisions occur when the channel assignment is poor.

Fact of simulating bidirectional traffic ($r_{T_gen}=25/75$) adds interferences to the network as dynamic interfaces of all nodes are used to transmit over more channels compared to the case where only downlink is simulated. The minimum of R_{app} is 3.2Mbps which is cumulative R_{app} for all of MAPs active.

The interferences connected with fact of using bidirectional traffic decrease the possible to achieve application data rate compared to unidirectional one. For example unidirectional chain scenario achieves $R_{app}=24.49$ Mbps, for 3 hops chain, utilizing 4 channels. In active nodes study the case where only 1 MAP is active can be thought of as chain scenario. The nodes that do not forward signal are not transmitting so it can be assumed that they are not there so it looks like chain one with 3 hops

utilizing 11 channels with bidirectional traffic. This is presented in Figure 4.47. Channels assigned to static interfaces are orthogonal ones. R_{app} Per node is 17.58 Mbps together of uplink and downlink. The value of R_{app} is lower compared to unidirectional one. The issues regarding this case have already been explained before.

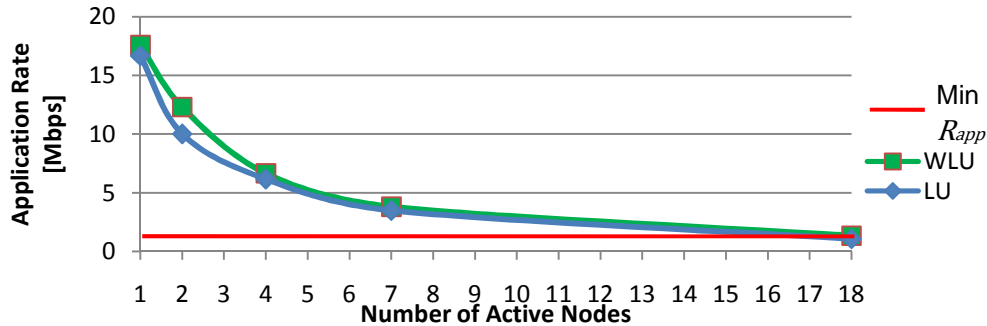


Figure 4.46 - Various Number of Active Nodes Transmitting in 3 Rings Scenario.

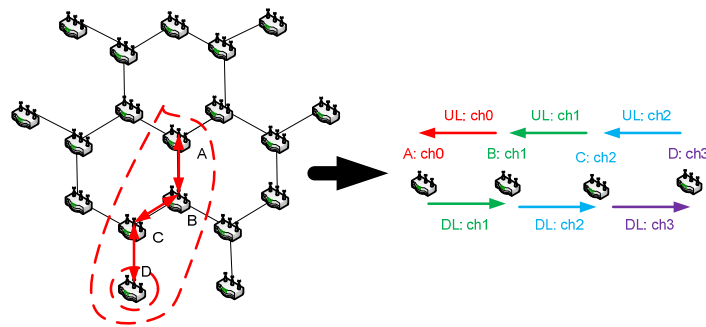


Figure 4.47 - One active node topology transition.

Delays from the study are presented in the Table 4.28. The fewer nodes are active the higher the delays become. This happens as with fewer active nodes, they achieve higher R_{app} , transmitting more packets, but through fewer paths. This congests those paths, increasing the delays. Moreover the transmitting or forwarding nodes are more vulnerable to collisions which increase the delays.

Table 4.28 - Delays for Various Number of Active Nodes in 3 Rings Scenario.

N_{n_active}	average delay[ms]			
	LU	LU Std. Dev.	WLU	WLU Std. Dev.
1	37.0	42.0	31	9.0
2	9.3	8.1	8	0.2
4	4.6	2.0	4	9.0
7	5.7	2.9	5	8.0
18	5.5	4.9	3.6	6.0

Table 4.29 - Trend Equations and Correlations for Number of Active Nodes Study.

Number of Active Nodes (N_{n_active}) vs:	Equation	R^2
R_{app} : WLU	$R_{app} = 20.73 \times N_{n_active}^{-0.9}$	0.982
R_{app} : LU	$R_{app} = 19.08 \times N_{n_active}^{-0.93}$	0.978

4 rings

In the 4 rings scenario the results can be divided in 2 groups, as the network was showing very poor performance with more than 5 nodes transmitting at the same time. That is why the cases with $N_{n_active} > 5$ where analysed with the same $R_{appoffered}$ and the delay, together with PER was evaluated. The second group is $N_{n_active} < 5$ where some connectivity has been achieved and the normal evaluation of performance has been made. Active nodes are picked up randomly, with the attention to keep the equal distribution of nodes among all rings.

As one can see from results in Table 4.30 the performance of the network shows satisfactory level only for $N_{n_active} \leq 4$. This happens as the OPNET interference area is 1000m and the collisions connected with transmission on the same channel are very high. Even though not all the nodes are active but still, some not active nodes need to be used to forward the traffic, causing interferences. The selection for the case of $N_{n_active} = 4$ is presented on Figure 4.48, together with example of the channels number assigned to the important nodes.

As one can observe from Table 4.30 the lower the number of active nodes is the better the performance becomes, the delay is decreased and the packet loss as well. The explanation is simple, as the fewer nodes transmit the lower interferences are present.

Table 4.30 - Results from Number of Active Nodes Study in 4 Rings Scenario.

	WLU					LU				
	[%]		[ms]		[Mbps]	[%]		[ms]		[Mbps]
N_{n_active}	loss	Std. Dev.	τ_{max}	Std. Dev.	R_{app}	loss	Std. Dev.	τ_{max}	Std. Dev.	R_{app}
15	7.8	1.2	32.7	12	0.01	7.0	0.8	33.0	11	0.01
10	6.1	1.2	26.6	20	0.01	6.6	1.1	31.0	17	0.01
6	2.9	2.8	6.6	4.4	0.01	2.4	2.1	6.4	5	0.01
4	0.5	0.3	8.1	5.4	5.22	0.4	0.3	5.9	6.2	4.00
3	0.7	0.3	6.9	0.4	5.22	0.6	0.4	4.3	2.1	4.44
2	0.6	0.3	5.4	2	5.00	0.6	0.1	2.6	1.5	4.62
1 (pessimistic)	0.02	0.2	7.8	1	22.64	0.1	0.4	2.1	2.1	6.32
1 (optimistic)	0.02	0.2	7.8	1	22.64	0.01	0.01	8.5	1.9	22.64

For the case of $N_{n_active} \leq 4$ the nodes behaving as active are respectively (Figure 4.48):

- Nodes D, K, H and AA for $N_{n_active} = 4$,
- Nodes K, H and AA for $N_{n_active} = 3$,
- Nodes H and AA for $N_{n_active} = 2$,
- Node AA for $N_{n_active} = 1$.

The gradual improvement of the application data rate achieved because of the active nodes decrease explains why the network is not performing well when all of the nodes in 4 rings scenario are transmitting. With the large number of nodes, the OPNET interference area of 1000m and channel number of 11 are not allowing for good channel reuse, the network is not performing at the satisfactory level.

As one can observe from the Figure 4.48 the channels are assigned in the way that the interferences should not be present when forwarding the packets from the central Gateway Node A to the node AA, which is the only one active for $N_{n_active} = 1$. That is why the available application data rate for the 4th ring node is 22.64Mbps, which is 92% of maximum theoretical application data rate. This situation is similar to the chain scenario, where for each hop there is orthogonal channel available. For the WLU UF this channel assignment is happening in all of the simulations made. For LU this is called optimistic channel assignment, as it happens as well.

When the same scenario, with $N_{n_active} = 1$ but using LU UF the channel assignment looks differently. In half of the cases on the path from Gateway to the Node AA two identical channels are being assigned. This creates a lot of collisions, as for example in chain scenario with 5 hops and 3 channels. As a result the $R_{app} = 6.32$ Mbps. However when the assignment of channels is optimistic the LU manage to assign orthogonal channels to all of the nodes on the path Gateway-Node AA and the $R_{app} = 22.64$ Mbps.

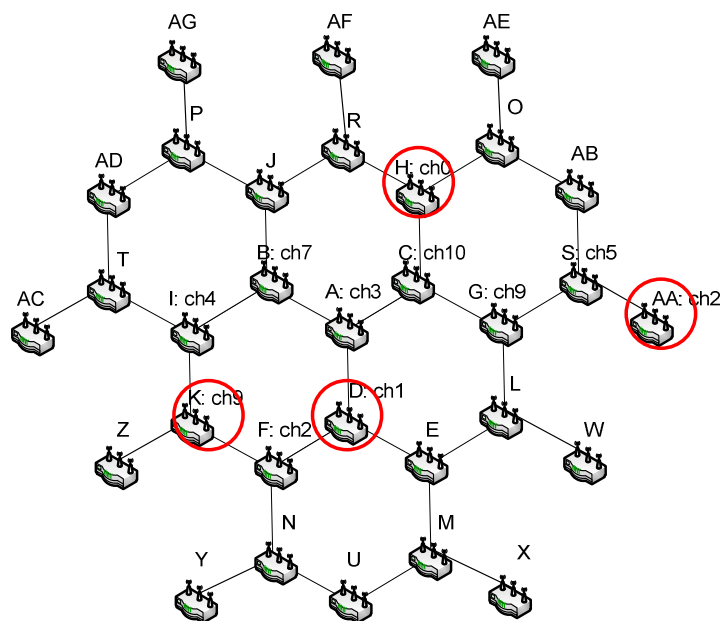


Figure 4.48 - Active Nodes in 4 Rings Scenario, WLU channel assignment.

Chapter Five

Conclusions

This chapter finalises this work, summarising conclusions and pointing out aspects to be developed in future work

This thesis focuses on comparison and performance evaluation of multihop, multi-radio wireless backbone networks, based on IEEE 802.11a system. Because the nodes in this networks use various channels two functions that assign the channels to the nodes has been evaluated. Influence of different input parameters has been studied and its impact onto the radio channel assignment algorithms. The goal was to find the setup that provides maximum application data rate to the user with the minimal usage of radio resources.

Wireless Mesh Networks are technology that allows building self-organising and self-healing networks. WMNs allow to extend the connectivity area by using only one internet gateway and relaying the signal through multihop path. Nodes can be equipped in several interfaces on which access services can be granted to client nodes and on the other ones forwarding can be made. As a natural consequence of this the nodes closer to the gateway will be more heavily congested with traffic. Several applications for WMNs technology can be applied which mainly focus on granting the connectivity over terrain without cable infrastructure, creating ad-hoc emergency network and many more. Any kind of wireless communication system can be used to deploy WMN. In this work, popular and cost-effective IEEE 802.11a system is used.

The model of the network that main studies have been conducted on is a hexagonal topology network which is divided into Rings of nodes. Ring is a group of nodes that is within the same distance from the gateway in terms of hop count. The nodes have got maximum 3 one-Hop neighbours around.

The node model has been adopted from [4]. The nodes are equipped with 2 radio interfaces, the static and dynamic interface. Both interfaces change channels that they transmit and receive on periodically. The static interface changes the channel each 3s and the dynamic interface each 0.1s if there is a packet to be sent on the particular interface. The specially developed link layer manages all the packet scheduling and is transparent to 1st and 3rd layer of protocol stack in the node. Each node maintains the table, where its neighbours channel assignment is periodically updated. The size of the table is dependent on the size of *k_neighbourhood* area which states how many hops away the node is evaluating the channel assignment.

The channels are assigned according to the evaluation that is made by an usage functions implemented in the Link Layer of a node. Two functions are implemented. Former one counts the nodes using particular channel in the neighbourhood and assigns the one used the least times. The latter does the same but also evaluates the nodes by their distance to the gateway. The closer node is to the gateway the more important it is because it has to forward more traffic. The more important nodes` channels are rated higher and their total evaluation score is higher as well. This makes more important nodes` channels be reused less number of times.

OPNET Wireless Suite 15.0A software is used for the simulation purposes. The simulations are run with two quality indicators. In all of the analysed simulations the goal is to find the highest application data rate offered for each node that assures fairness. The traffic offered for each node is gradually increased until the packet loss exceeds 1% of offered traffic or the delays go beyond 100ms. The highest value of offered traffic, which depends on packet interarrival values, that assures both conditions to be true is taken as a result. All of the traffic was scheduled each time after the

convergence period of the network has passed and the traffic was lasting for 60s each time. As this is backbone network and the traffic is continuous without significant changes throughout the time the period is enough to reach stable results. The longer values of simulation time were checked as well, and did not present any differences.

The first study was to compare theoretical calculations to practical values from OPNET of application data rate possible to achieve in single hop, two nodes network. All 4 mandatory supported data rates of 802.11a system have been evaluated. The highest data rate of physical interface – 54Mbps resulted in $R_{app}=30$ Mbps of application traffic. This values are used as maximum application data rate that each gateway interface can forward when different data rates are set. It is the maximum value of aggregated traffic that cannot be exceeded when traffic from all nodes is summed up for a semidirectional traffic case. For a bidirectional traffic the value is double.

As the second chain topology study the benchmark on CSMA/CA access scheme has been made to analyse the amount of traffic that can be forwarded using RTS-CTS mechanism and without it for maximum supported data rate. The topology was the same- single hop, two nodes network. This gave the results that with RTS-CTS mechanism the maximum $R_{app}=24.49$ Mbps per one node and one interface, while without it $R_{app}=30.00$ Mbps. This gave the reference value to which later all the theoretical and practical calculations has been referencing to.

The next study was to evaluate the interference level depending on the distance between the nodes transmitting on the same channel, without being aware of that. As the networks analysed are going to be deployed as backbone networks in rural scenarios, mainly the line of sight is going to be maintained. Thus the free space model was used for power level calculations. Large theoretical and OPNET interference distances have been found of 5.9km and 1000m respectively. This infers that when the transmissions on the same channel are scheduled those need to be controlled. The high difference between two values are because when evaluation OPNET interference range 1% PER is allowed, while in theoretical studies no packet can be lost.

The last of chain topology studies has evaluated the influence of number of used channels for various number of hops in a chain. This was to understand how interferences are generated and what are expectable application data rates to be achieved. As it has been studied the most important factors for interference control are the channel reuse distance and number of channels available to assign. For the unidirectional downlink traffic and the M-R nodes utilising 5 channels the value of 24Mbps is achieved, almost matching One-Hop theoretical maximum. For the 5hops chain utilising 4, 3, 2 and 1 channels the results were 4.00, 3.33, 2.93, 0.3Mbps respectively. Each of the chain topology was unidirectional scenario in order to analyse the decrease of performance observed due to increase in number of hops.

Before conducting Ring studies theoretical maximum for various ring topologies has been calculated. For unidirectional traffic and 2, 3, 4 Ring scenarios the theoretical application data rates are 2.72, 1.36 and 0.81 Mbps respectively.

The study of transmitted power level has been conducted. For 3 topologies with increasing number of

rings from 2 to 4 were used for the study. The impact of transmission power level has been evaluated on those scenarios. The results showed that with the set number of channels the power levels should be adjusted to the size of the network. For 2 rings scenario the lowest power level of 200mW is optimal resulting in application data rate achieving 96% of theoretical maximum, while for 3 rings intermediate power level of 530mW is optimal resulting in 90% of theoretical maximum. Because freespace model has been used, the interference level do not allow to forward packets in 4 ring scenario. Too many nodes transmitting on the same channel cause collisions. When the power level has been raised to the maximum 1000mW the performance went up to 58% of theoretical maximum.

The comparison of handshaking mechanism CMA/CA with RTS-CTS and without RTS-CTS has been conducted as next. Various traffic characteristics were analysed, where proportion of DL and UL traffic has been changed. The results showed that the RTS-CTS mechanism is useful for the cases where UL traffic is forwarded. The more UL traffic is in the UL/DL ratio, the better RTS-CTS was performing, reaching 2.5 times better performance for 100%UL case. For only the UL traffic the CSMA/CA with RTS-CTS results in 2.26Mbps, while without RTS-CTS it is 0.86Mbps. This is because when UL traffic direction is scheduled the contention for medium is via the same channel by all competing nodes, what allows controlling and scheduling the transmissions. In downlink case the RTS-CTS is not useful as simply the transmissions are on different channels, so there is no possibility to receive the packets.

For the $K_{\text{Neighbourhood}}$ study only 2 and 3 ring topologies were taken as 1 ring would not present any relevant results as only 4 nodes are there. The topology of 4 rings was not taken either as for given transmission power value (200mW) it does not show the satisfactory performance. The $K_{\text{Neighbourhood}}$ has been varied from 2 until 4 and its influence on application data rate, e-2-e delay and convergence time has been studied. The results show that it is worth to set the $K_{\text{Neighbourhood}}$ to the maximum. In 2 ring scenario when the 50/50 traffic is used, although the delays are almost highest from all analysed - 14.5ms, the achieved application data rate is 77.4% of theoretical maximum. In 3 ring scenario, using $K_{\text{Neighbourhood}}$ of 4 results in 1.41Mbps with delays of 5.6ms. In 50/50 traffic case the application data rate is 51.9% while for 100%DL traffic it is 84% of theoretical maximum. The disadvantage of high $K_{\text{Neighbourhood}}$ parameter is that the convergence time is increased, which may be a problem when nodes will be appearing and disappearing to and from the network.

The next study evaluated both Usage Functions for varying number of channels in 2 and 3 ring scenarios for DL traffic only. The results were delays, PER and application data rates. The conclusion is drawn that below certain number of channels available to use (for 2 rings -4 channels, for 3 rings-7channels) it is more advantageous to use LU. Above those values, when more channels can be used, it is better to use WLU UF. In 2 ring scenario, using 4 channels, LU usage function reaches 88% and the WLU reaches 90% of theoretical maximum. When 3 ring scenario, 7 channels, is considered the LU reaches 46% while WLU 55% of R_{app_max} . WLU makes the nodes not to use GW`s and 1st ring node`s channels and when there are not enough channels to distribute among other nodes the performance decreases compared to LU. However the GW`s static channel is not used efficiently

when using WLU as only DL traffic is present. In the DL case the interesting issue arises in 2 ring scenario, for 3 channels and LU UF. The unexpected increase of application data rate is observed as the static interface is used for transmitting the packets to a One-Hop neighbour with static interface fixed on the same channel. Normally fixed interface is used for receiving so when traffic mix is considered this would not happen.

The same study as described before has been conducted but for UL traffic. The same dependency as before is present, where for number of channels less than 4 or 7 for 2 and 3 rings topology respectively, it is better to use LU UF. In 2 rings scenario, 4 channels LU reaches 44%, while WLU reaches 83% of theoretical maximum. In 3 ring scenario, 7 channels the LU reaches 38%, while WLU 80% of theoretical maximum. This is happening as in uplink traffic the child nodes are competing to transmit to parent nodes in one channel and each time it is better to protect the GW channel by not reusing it too often.

Using 2 ring and 3 ring scenario the influence of traffic generation ratio is analysed on application data rate and delays. In 2 ring scenario when using 100% DL traffic the performance is better than 100% UL. This issue has been explained already. When bidirectional traffic is considered and 50/50 traffic characteristics, UFs reach 52% for WLU and 44% of theoretical maximum for LU. When the traffic is 25/75 the performances are 49% and 39% for WLU and LU. If traffic is distributed in a more equal manner, using the DL and UL interface equally results in better performance.

In 2 ring scenario the delays present the distinction between usage functions in each of traffic cases, in opposite to application data rate studies. In unidirectional case the delays present in 100% UL scenario are almost 10x times higher (40ms) than in 100% DL scenario (3.8ms). This is because in UL scenario child nodes need to compete for the medium access between each other. The LU usage function presents better performance in DL case where it reaches 3.8ms, while WLU 6.3ms. WLU however is performing better in 100% UL case reaching 31ms, compared to 41ms of LU. In DL the transmission is in each case on separate channel so the delays can be greatly reduced. In 50/50 traffic case the difference is for 50/50 traffic case where using WLU results in delays of 13ms while LU reaches 33ms. It happens because while using 2 DL and UL traffic and in fully congested network case the WLU's strategy of protecting the more important channels is beneficial.

In 3 rings scenario as the number of channels is not sufficient to distribute separate channel for each static radio interface the differences in application data rates start to be present. As in a few cases already studied when the UL traffic is sent the WLU is performing better than LU, where WLU achieves 1.14Mbps and LU 1.04Mbps. In 3 rings scenario the application data rates do not reach the theoretical maximum. In DL case both UF reach the same 1.14 Mbps of application data rate. In both semidirectional cases the WLU is better in terms of R_{app} . In 25/75 scenario WLU presents performance on the level of 1.33Mbps compared to 1.06Mbps of LU. In 50/50 scenario WLU shows $R_{app}=1.41$ Mbps, while LU 1.2Mbps/

The delays are highest for 100% UL as the RTS-CTS messages are not successfully received and cause collisions. For WLU $\tau_{max}=12$ ms, while for LU $\tau_{max}=8$ ms. In bidirectional traffic cases the delays

are higher for both characteristics because more traffic is possible to be forwarded than in unidirectional case.

While studying active nodes scenario the reason for poor performance of 4 ring scenario has been revealed. As the number of active nodes was gradually decreased the number of used interfaces and number of used channels has been decreased as well. When the number of active nodes has been decreased to 4 the connectivity started to be possible, with the application data rate of 4Mbps. This situation is because the number of interfering nodes has been decreased to the level when level of SINR allowed to successfully receive the packet.

Moreover in LU usage function case, when the 1 active node has been used the issue of bad channel assignment aroused. As in this case the only communication is between 2 nodes (GW and Active Node) the communication path can be decreased in size to the chain scenario. As in the chain scenario, here the LU usage function is not aware of the distance to the nodes that use the same static channel and thus it can assign the static channel of a node closer away than other rated likewise. This is not present when using WLU usage function as it distinguishes the distance of a node to the gateway and rates the channels according to this distance. Using WLU usage function is a solution for unexpected decrease in performance described in chain scenario. In one Active Node scenario the WLU achieves $R_{app}=22.64\text{Mbps}$, while LU depending on channel assignment varies from 6.32Mbps to 22.64Mbps.

The main conclusion drawn from the simulations is that when WLU usage function is used the performance is better. It is advised to use it in realistic scenarios to achieve optimal performance with networks that consist of maximum 3 rings. For larger networks the transmission power must be maximum possible with low activity of nodes.

The free space propagation channel model, used in the work is unrealistic for the type of scenario 802.11a technology is intended. The used value of α_{pd} set to 2 is not appropriate. An urban environment considers an α_{pd} of 3.3, and would be more appropriate value to use. The interference as well as transmission range would decrease resulting in larger application data rates per each node. The free-space model could be considered (but still it is erroneous) if there was line of sight and no obstacles, which could be achieved if the antennas would be mounted properly.

For a 54 Mbps data rate the SINR is very high, resulting, in an extremely large interference distance (1000 m), compared to the node to node distance (100 m). The interference distance defines a region where simultaneous transmissions on the same channel result in collisions. This means that in this area the same channel cannot be reused. For such an environment with nodes each 100 m aside, a smart channel distribution between nodes is useless. As the studies with lower than 54Mbps data rate has been conducted, the only solution to reuse the channels less hops away is to set the α_{pd} to the higher value.

The value of PER set to 1% is too demanding. It enforces the $P_{SINR_{min}}$ to be higher than for example for PER set to 10%. Using higher value of PER would result decreasing the interference ranges and making the scenarios more realistic ones.

As some issues aroused during the conducted studies the following suggestions for future work are presented:

- Conducting the studies with nodes switching on and off dynamically,
- Adjusting the Link Layer to transmit on static interface whenever it is not busy with receiving the transmission from other nodes.
- Adjusting the weight distribution in WLU UF and checking the performance,
- Conducting studies with various services, that will vary the packet sizes and the overall performance of the network,
- Improving the Link Layer to prioritise the traffic, for at least real time and non real-time mechanism.

Annex A

CSMA/CA Handshake Mechanism

This annex is providing information on CSMA/CA Handshake Mechanism.

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [14] protocol is designed to reduce collision probability between multiple STAs accessing the medium. When the STA is going to transmit it senses the medium to determine if the medium is busy or idle. A collision may occur when two stations at the same time detect the idle channel and start transmitting. A transmitting station must wait required period of time, a Direct Control Function Interframe Space (DIFS), before attempting to transmit, which equals round trip propagation time plus the medium access contention time. If the medium is determined busy the STA shall defer until the end of the current transmission.

An optional four frame exchange scheme may be used to further increase the reliability, Request To Send-Clear To Send (RTS-CTS) [14], that Figure A.1 shows. RTS packet contains information about time needed by the node to occupy the channel. RTS is sent from a source station to a destination one, which replies with a CTS frame thus reserving the medium for particular transmission. After this data exchange is made finishing always with ACK. That prevents collisions, because each node is aware of the transmission before it occurs. The nodes that receive CTS which is not designated to them set the Network Allocation Vector (NAV) during which they defer from sensing the channel in order to reserve the time for other node to transmit the packet. Before sending the RTS frame the node must sense the channel. The differences between CSMA/CA and RTS-CTS are presented on Figure A.2.

If the channel is detected as idle the station needs to wait certain amount of time, sensing the channel. If during this period no transmission is run the node can start transmitting RTS frame. The duration of this period is called backoff period. Backoff time is calculated on the basis of the Contention Window (CW) [14] which is a number of aSlotTimes that a node needs to prevent from transmitting. At the beginning the backoff a random number from $(0, CW_{min})$ is generated where for 802.11a CW_{min} is 15. When the channel is sensed as occupied the CW is doubled and new random number is generated. This is done until CW reaches maximum value CW_{max} that for 802.11a is 255.

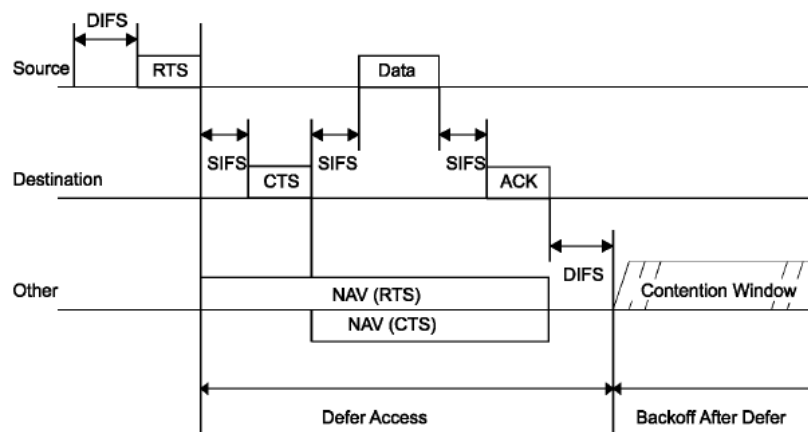


Figure A.1 - RTS/CTS/ACK/data and NAV setting (extracted from [25]).

Concerning timing, the time between two MAC frames is called the Interframe Space (IFS) [14], 802.11 defining four different IFSs: the Short Interframe Spaces (SIFS), the Point Coordination Function interframe Space (PIFS), the Distributed Coordination Function Interframe Space (DIFS) and

the Extended Interframe Space (EIFS). These interframes do not depend on the channel data rate, but only on the used transmission scheme. A slot duration (aSlotTime) is used to calculate the IFs, and aSlotTime is used during the Collision Avoidance (CA).

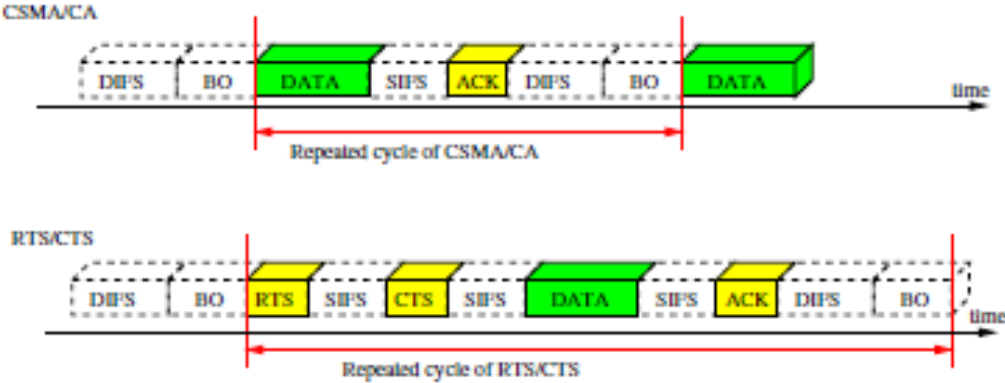


Figure A.2 - Packet Exchange Structure for CSMA/CA and CSMA/CA with RTS-CTS (extracted from [25]).

Annex B

IEEE 802.11 Standard

Features

This Annex is presenting the main features of IEEE 802.11a standard, that is used as wireless communication system in this work.

Various 802.11 standards have various features that are presented in Table B.1. As seen in the Table B.2, minimum Power of received signal (P_{min}) and minimal Signal to Interference and Noise Ratio ($r_{SINR_{min}}$) needed to receive a 1000byte frame with more than 90% success probability has been defined [14]. 802.11g hardware is fully backwards compatible with 802.11b and those are most widely used. Out of 13 channels possible to use, there are only 3 non-overlapping channels in 2.4GHz spectrum band. In the 5.8GHz band however the number of non-overlapping channels is 19 (depending on the continent [2]), what is presented in the Table B.3 which enables higher density of nodes compared with 2.4GHz band.

Table B.1 - IEEE 802.11 standards main features (extracted from [14]).

Name	Number of orthogonal channels	Frequency Band [GHz]	Data Rate [Mbps]	Application Data Rate [Mbps]	Typical outdoor range [m]	Transmission	Max. Power [mW]
802.11a	19	5.0	54	~27	120	OFDM	1000
802.11b	3	2.4	11	~5	140	CCK	100
802.11g	3	2.4	54	~27	140	CCK OFDM	100
802.11n	3 or 12	2.4 or 5.0	600	~144	250	OFDM	50

Table B.2 - IEEE 802.11a, 802.11g OFDM features (extracted from [14]).

R_{NB}	PHY mode MCS	FEC	P_{min}	$P_{SINR_{min}}$
Mbps			dBm	dBm
6	BPSK	1/2	-82	18
9	BPSK	3/4	-81	21
12	QPSK	1/2	-79	22
18	QPSK	3/4	-77	25
24	16-QAM	1/2	-72	25
36	16-QAM	3/4	-70	32
48	64-QAM	2/3	-66	34
54	64-QAM	3/4	-65	35

The 19 available channels to use in 802.11a 5GHz band are the ones designated by European Telecommunications Standard Institute (ETSI) what is presented in Table B.3. This table is particular for Europe, where for the same bands for USA and Japan a few other channels are possible to use. Some of the channels are said the be used only indoors and the allowed transmitted power level is decreased.

Table B.3 - ETSI channel frequencies in 802.11a 5GHz band.

ETSI type	Channel Id	Frequency	Maximum Allowed Power Level
		MHz	dBm
indoor	6	5 180	23
	40	5 200	
	44	5 220	
	48	5 240	
	52	5 260	
	56	5 280	
	60	5 300	
	64	5 320	
indoor & outdoor	100	5 500	30
	104	5 520	
	108	5 540	
	112	5 560	
	116	5 580	
	120	5 600	
	124	5 620	
	128	5 640	
	132	5 660	
	136	5 680	
	140	5 700	

Annex C

Interference Distance Calculation

This annex is providing the insight into calculations made to obtain interference distance.

- Equations used for calculations:

$$P_{rx[dBm]} = P_{tx[dBm]} - L_{[dB]}$$

$$L_{p0[dB]} = 20 \log(d_{[km]}) + 20 \log(f_{[MHz]}) + 32.44$$

$$L_{[dB]} = L_{p0}(d_{0[km]}) + 10 \times a_{pd} \times \log(d_{[km]}/d_{o[km]}) + \Delta L_{[dB]}$$

$$SINR(M_r \leftarrow M_t) = \frac{P_r(M_r \leftarrow M_t)}{P_{N_0} + \sum_{M_i \in J} P_r(M_r \leftarrow M_i)} \geq P_{SINR}(R)$$

- The propagation is in freespace:

$$a_{pd}=2$$

$$\Delta L_{[dB]}=0$$

For $P_{tx}=200mW$, $P_{tx}[dBm]= 23dBm$:

Nodes are located

$$d_{0[km]} = 100m$$

$$d_{n2n}[km] = 109m$$

$$f_{[MHz]} = 5500$$

- Putting the values, that are used in each scenario, into equations:

$$L_{p0[dB]} = 20 \log(d_{[km]}) + 20 \log(f_{[MHz]}) + 32.44 = 20 \log(0.1) + 20 \log(5500) + 32.44 = 87.25[dB]$$

$$\begin{aligned} L_{[dB]} &= L_{p0}(d_{0[km]}) + 10 \times a_{pd} \times \log\left(\frac{d_{n2n[km]}}{d_{o[km]}}\right) + \Delta L_{[dB]} = 87.25 + 10 \times a_{pd} \times \log\left(\frac{d_{n2n[km]}}{d_{o[km]}}\right) + 0 \\ &= 87.25 + 10 \times a_{pd} \times \log(d_{n2n[km]}) - 10 \times a_{pd} \times \log\left(\frac{1}{d_{o[km]}}\right) \end{aligned}$$

- The reception is possible when:

$$\frac{P_r(M_r \leftarrow M_t)}{P_{N_0} + \sum_{M_i \in J} P_r(M_r \leftarrow M_i)} \geq P_{SINR}(R)$$

- Assuming only one interferer and neglecting the noise from other non existing nodes:

$$P_{n2n}[dBm] - L_{n2n[dB]} - (P_{n2n_i}[dBm] - L_{n2n_i[dB]}) \geq P_{SINR}(R)$$

- As interferer and transmitting node transmit with the same power they discard each other and only losses are taken into consideration:

$$L_{i[db]} - L_{n2n[db]} \geq P_{SINR}(R)$$

$$\left(87.25 + 10 \times a_{pd} \times \log(d_{i[km]}) - 10 \times a_{pd} \times \log\left(\frac{1}{d_{o[km]}}\right)\right) - \left(87.25 + 10 \times a_{pd} \times \log(d_{n2n[km]}) - 10 \times a_{pd} \times \log\left(\frac{1}{d_{o[km]}}\right)\right) \geq P_{SINR}(R)$$

$$10 \times a_{pd} \times \log(d_{i[km]}) - 10 \times a_{pd} \times \log(d_{n2n[km]}) \geq P_{SINR}(R)$$

$$\log(d_{i[km]}) - \log(d_{n2n[km]}) \geq \frac{P_{SINR}(R)}{10 \times a_{pd}}$$

$$\frac{d_{n2n_i[km]}}{d_{n2n[km]}} \geq 10^{\frac{P_{SINR}(R)}{10 \times a_{pd}}}$$

$$d_i \geq d_{n2n} \times 10^{\frac{P_{SINR}(R)}{10 \times a_{pd}}}$$

Annex D

Various Number of Channels in 2 Ring Scenario- Results.

This annex is presenting some figures less relevant to the work..

Table D.1 - Relative to Theoretical, Application Data Rate for Various Channel Number in 2 Rings Scenario, DL only.

		R_{t_app} [%]				
Single Radio		22				
Multi Radio N_{ch_ort}		2	3	4	7	11
UF	LU	74	88	88	98	99
	WLU	49	63	90	98	99

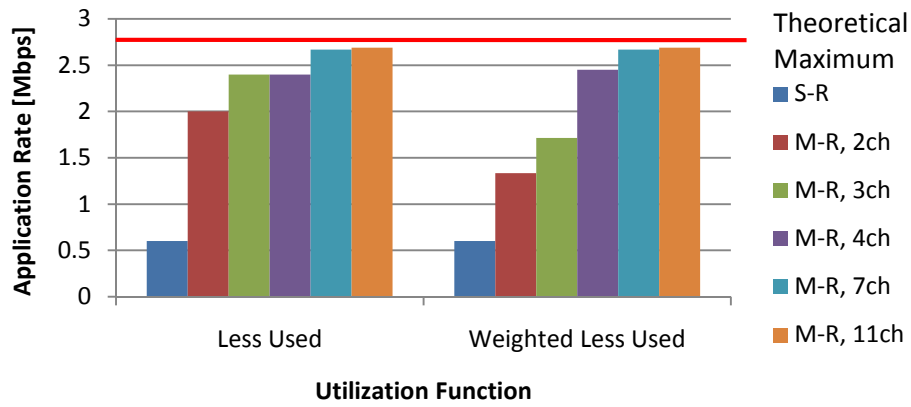


Figure D.1 - Per Node Application Data Rate for 2 Rings Scenario, DL only.

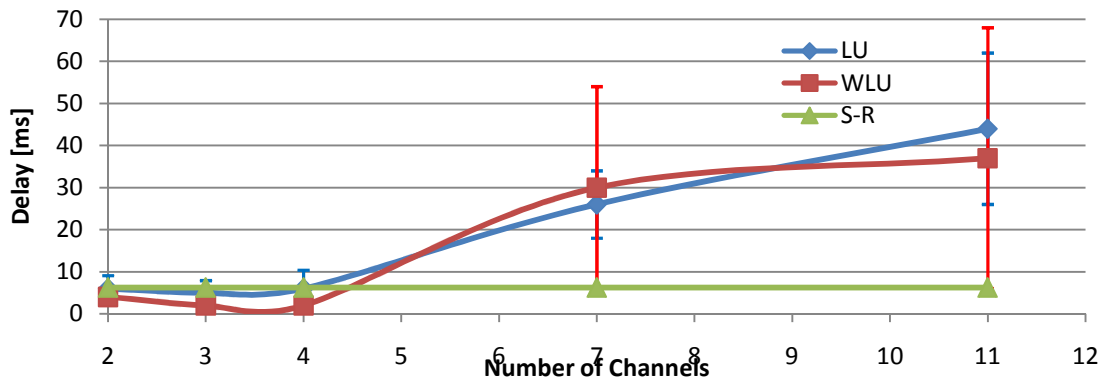


Figure D.2 - Delay in Channel Study of 2 Rings Scenario, DL only.

Table D.2 - Relative to Theoretical, Application Data Rate for Various Channel Number in 2 rings Scenario, UL only

		R_{t_app} [%]				
Single Radio		8.8				
Multi Radio N_{ch_ort}		2	3	4	7	11
LU		22	37	44	85	86
WLU		34	44	83	86	86

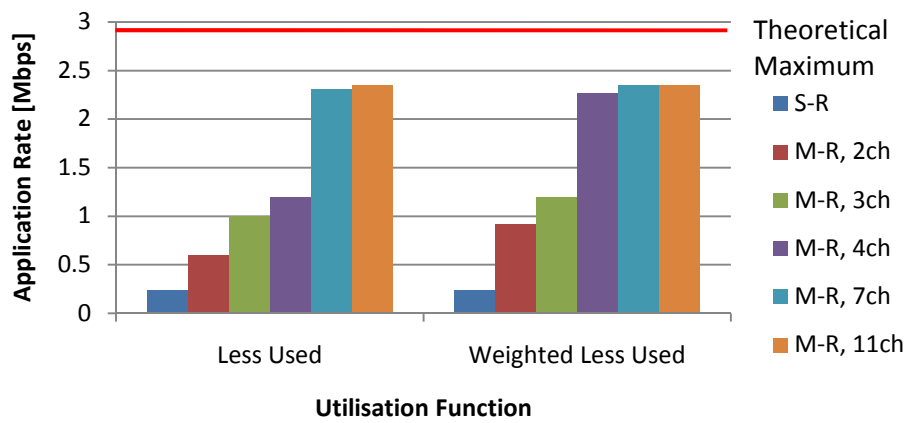


Figure D.3 - Channel Number Study for 2 Ring Scenario UL only.

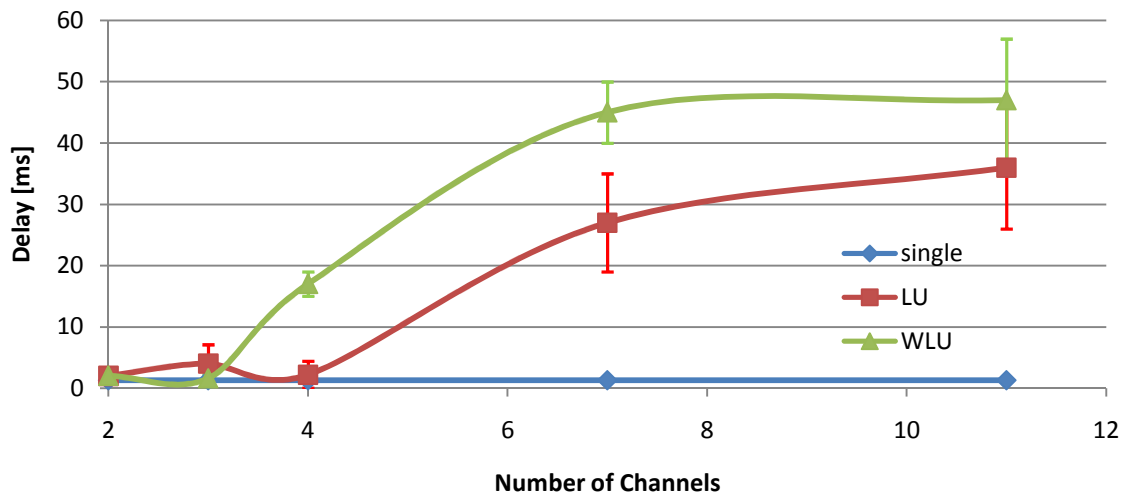


Figure D.4 - Delay For Channel Number Study in 2 Rings Scenario UL.

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