Radio Resource Management Strategies for Wireless Mesh Networks

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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. A network model over which the main studies have been conducted is a hexagonal topology. Two radio channel usage evaluation functions are analyzed. A several simulations using OPNET software has been run and revealed following results. Using freespace propagation model in a 4 ring network where nodes utilise 7, out of maximum 11, orthogonal channels it is possible to reach connectivity only with the transmission power of 1000mW. Wherever the uplink traffic is scheduled it is beneficial to use CSMA/CA with RTS-CTS handshake mechanism in the multichannel network. When only DL is used the results are better without RTS-CTS. 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 utilisation 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 utilisation function is performing better for all number of channels. The theoretical maximum in uplink is not reached due to imperfections of RTS-CTS.**

Keywords- Wireless Mesh Networks; WLANs; Radio Resource Management; Radio Channel Assignment;

I. INTRODUCTION

In recent years internet access has became an asset that is of a value for information societies. Deploying wired networks in each area is costly and inefficient if very high capacities are not in demand. Building a wireless networks is an interesting alternative. It is possible to deploy a wireless backbone network, where access point (nodes) not only provide access services for client nodes but also relay packets of other nodes by means of wireless multihop transmission. Such a network is called Wireless Mesh Network (WMN) [1].

WMN networks can be built over any wireless communication system which allow usage of at least several orthogonal transmission channels. In this work IEEE 802.11a [2] system is used, which allow to utilize 11 channels around 5GHz spectrum, with data rates up to 54Mbps. WMN network is self-organizing and self-healing by means of nodes automatically discovering and maintaining wireless links.

The key issue while using WMNs is channel assignment. It influences the application rates possible to provide for each node in the network by decreasing the interference level. Each node before assigning the channel evaluates the usage of each channel in the neighbourhood. The influence on performance of the network of two utilization functions (UFs), Less Used (LU) and Weighted Less Used (WLU) is evaluated in this work. Node model, together with UFs implemented has been derived from [3]. Moreover number of channels N_{ch}, transmission power P_{tx}, size of neighbourhood $K\_Neighbourhood$, traffic characteristics and number of active nodes N_{n_act} is evaluated in this work as well for different sizes of network.

The document is structured as follows: I – Introduction; II – Sate of the Art; III – Algorithms And Models; IV – Scenarios and Results; V – Conclusions

II. STATE OF THE ART

A. *Wireless Mesh Networks*

The main advantage of WMNs is the self-organisation and self-management. Nodes communicate with each other, exchanging the information about other nodes in their neighbourhood. Usually there is one gateway node (GW) in the network that is equipped with high capacity connection to the internet. Nodes forward the packets for other nodes so that the internet connectivity is reached by each node. One-Hop neighbourhood of a node is area limited by radius of successful transmission range. Nodes inside this area that are closest to the node are one-hop neighbors of a node. Nodes that are not one-hop neighbors are interferers.

The architecture of WMN can be divided in 3 types. Backbone network is consisting of nodes that offer access services for clients over one interface, and forward the packets for other nodes over one or more additional interfaces. In the client network nodes communicate in ad-hoc manner exchanging packets between each other and also with the gateway node. Hybrid network is the most applicable one that connect both types of the network.

WMN suffer from application rate decrease because of nature of multihop transmission. In chain topology for example, as presented on Figure II.2, when node 1 is transmitting to node 2, other nodes are not able to receive data correctly when the transmission is on the same channel. The decrease in achieved application rate is presented in TABLE II.1 and [4].

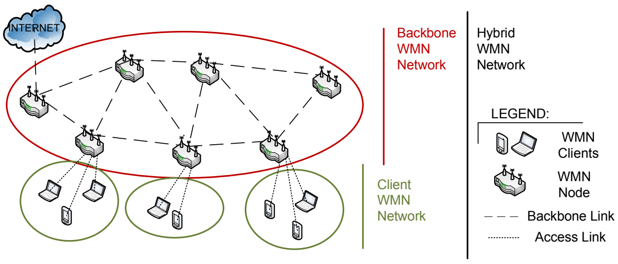

Figure II.1 Architecture of WMN (extracted from [1]).

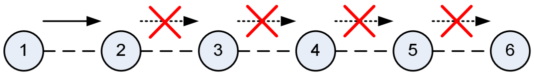

Figure II.2 Chain Topology.

TABLE II.1 APPLICATION RATE DECREASE IN CHAIN TOPOLOGY.

Hops	**1**	**2**	**3**	**4**	**5**	**>5**
App. Rate	1	0.47	0.32	0.23	0.15	0.14
1/ hop	1	0.50	0.33	0.25	0.20	0.16

As each node in WMN backbone network is generating the same application rate to be forwarded another problem arises. It is named as fat-tree problem [5]. As the capacity of each radio interface in the network is the same, the one that central GW node uses is loaded the most. Each node in the network must be able to communicate with the same data rate, and when this state is achieved the network is said to be maxmin-fair. The problem is in distributing the load evenly to each node, no matter how many hops away it is from the GW. The maxmin-fair network is presented on Figure III.1, where nodes A and B are served with the same application rate T.

B. *WMNs in WLANs*

Implementation of WMN in this work is made over IEEE 802.11a system, which is prominent example of Wireless Local Area Network (WLAN). Hidden, deaf and exposed nodes are problems that are well known for WLANs. Assuming that the communication range is one-hop i.e. distance between nodes A and B on Figure III.2. Hidden nodes for transmitting pair A-B are nodes C and F, as those are not aware of transmission started in A. If either C or F starts to transmit the collision will occur in node B. To mitigate this problem RTS-CTS [6] handshake mechanism was developed. It introduces additional packets that need to be exchanged between node A and B in order to start a transmission. RTS-CTS packets are received by nodes C or F and those set the Network Allocation Vector (NAV) and defer from transmitting until the time predicted for transmission ends.

This however creates some issues. Node C is deaf when it cannot receive RTS-CTS messages. For example, when transmission D-E occurs many packets are sent. During this time when transmission B-A will start node C will not be able to receive RTS-CTS messages as those will collide with already ongoing transmission. After NAV connected with D-A transmission passes node C is not aware of transmission B-A and may start transmitting causing collision in B. Node C can be exposed when node D starts transmission to E. Node C sets NAV vector and cannot transmit, however its transmission to B should not cause collisions in node E.

The main problem under study in this work is optimal allocation of radio channels. Some Radio Channel Allocation (RCA) algorithms were studied: HMCP [7], LACA [8], MesTIC [9], CCC [10].

Main parameters Used for performance analysis are presented:

- $d_{tx[\mathrm{m}]}$ is a transmission range,
- $d_{i\_t[\mathrm{m}]}$ is a theoretical interference range [12],
- $d_{i\_o[\mathrm{m}]}$ is an OPNET interference range,
- $R_{[\mathrm{Mbps}],}$ nominal data rate of an interface,
- R_{app} application rate,
- $\tau_{max[\mathrm{ms}]}$ maximum delays of packets,
- $\tau_{e2e[\mathrm{ms}]}^{av}$ average packet delay,
- ${R_{app}}_{offered[\mathrm{bps}]}$ offered application rate,
- ${r_{app}}_{gen}$ application rate generation ratio i.e. traffic characteristics,
- R_{PER_max} maximum packet error rate.

III. ALOGRITHM AND MODELS

A. *Network and Node Model*

The network model used in this work has got some assumptions:

- Each node is connection point between backbone and access network,
- Only the backbone network performance is evaluated,
- Only one node is serving as a gateway,
- LOS is always maintained,
- Propagation conditions are time stable and known,

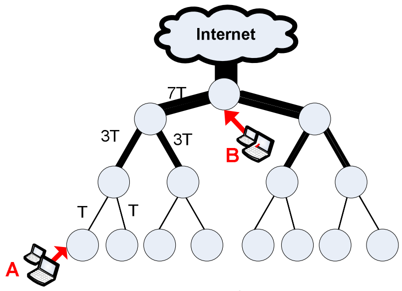

Figure III.1 Maxmin-fair Network.

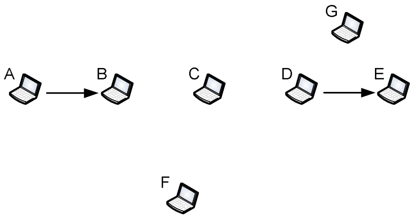

Figure III.2 Illustration for hidden, exposed and deaf nodes.

Moreover parameters defining network and nodes are introduced:

- Nodes are in d_{n2n} between their neighbors,
- Number of One-Hop neighbor nodes is N_{ohn},
- Total number of nodes in the network is N_n,
- Nominal data rate of interface is R,
- Number of orthogonal channels is N_{ch}
- Transmission power of interface is P_{tx}

The node model derived from [3] is equipped with 2 radio interfaces, dynamic one and static one. Each node fills and maintains Neighbor Table (NT) inside which it stores IP, MAC and Channel Number of One-Hop neighbors. Separate queues are assigned for each radio channel. If a packets needs to be sent it arrives from routing table with the next-hop node address. It goes through NT and arrives to a channel queue. Dynamic Radio interface goes in Round Robin way through each queue and transmits until the queue is empty or until maximum time $\tau_{dynamic}$ of transmitting over one interface has passed. Static interface is fixed on a channel relatively longer period of time τ_{static} receiving packets from other nodes. Each τ_{Hello} seconds, node broadcasts the Hello packet, where the information about its static channel, IP and MAC addresses of static channel is provided, together with Channel Usage Table (CUT). Each node by receiving those packets creates CUT where information about nodes using particular channels is stored. The CUT contains information about nodes $K\_Neibhbourhood$ hops away.

The maximum theoretical application rate that each node must have guaranteed to assure maxmin fairness is R_{t_app}. The factor that limits this value is capacity of GW radio interface, as shown on Figure III.1. The simple way of calculating the R_{t_app} is presented In (II.1), where no packet loss occurs.

$$R_{t\_app_{[\mathrm{Mbps}]}} = \begin{cases} R_{app}^{gw}/N_n \ for\ unidirectional\ traffic \\ 2 \times R_{app}^{gw}/N_n \ for\ bidirectional\ traffic \end{cases} \quad \text{(II.1)}$$

B. Radio Channel Allocation Algorithm

RCA studied in this work is derived from [3]. It focuses on decreasing the interferences and increasing the application rates achieved by each node. The algorithm is proposed for spontaneous and opportunistic radio channel assignment. It connects ideas from a few algorithms developed earlier:

- It uses static and dynamic radio interface like in HMCP [7]
- Creates, manages and sends Hello packets [9]
- Evaluates the channel usage in neighbourhood like [10]

Main functionalities of RCA are listed:

- Maintains CUT and NT
- Each $\tau_{dynamic}$ dynamic radio interface switches channel it transmits on
- Creates and broadcasts Hello packets
- Each τ_{Hello} node evaluates the channel usage inside $K_Neighbourhood$area and chooses for static interface the one that the usage is lowest
- Gateway announces itself so that each node is aware of the distance to the gateway

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

1. Activity A is calculated:

$$A(M_a, C_c) = \begin{cases} 1\ M_a\ has\ got\ C_c\ assigned\ in\ the\ NT \\ 0\ otherwise \end{cases} \quad \text{(II.2)}$$

where:

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

2. Utilisation U_T, of each channel used by all the nodes in the interference neighbourhood is computed. UF do it in different ways:

2.1. LU UF, simply counts the number of nodes using each channel:

$$U_{T\_LU}(X_m^{C_c}) = \sum_{M_a \epsilon X_m^{C_c}} A(M_a, C_c) \quad \text{(II.3)}$$

where:

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

2.2. WLU UF computes U_T in similar way to LU. It also counts 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 (II.4) 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.

$$W(N_{h_{gw}}(M_a) = \begin{cases} 1, for\ N_{h\_gw} = 0 \\ 1/\left(N_{ohn} \times 2^{(N_{h\_gw}-1)}\right)\ for\ N_{h\_gw} > 0 \end{cases} \quad \text{(II.4)}$$

$$U_{T\_WLU}(X_m^{C_c}) = \sum_{M_a \epsilon X_m^{C_c}} \left(A(M_a, C_c) \times W(N_{h_{gw}}(M_a))\right) \quad \text{(II.5)}$$

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 utilisation:

$$C = \{C_k, k\epsilon\{1, \ldots, N_{ch\_ort}\}: \min U_T(X_m^{C_c})\} \quad \text{(II.6)}$$

C. OPNET

All the simulations conducted throughout the work are made in OPNET Wireless Suite 15.0A. 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 Physical Layer Convergence Protocol (PLCP) overhead of the packet is always sent with the rate of 1Mbps to assure backwards compatibility with all of the 802.11 systems. 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. 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.

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:

$$R_{Op\_mac} = R_{Op\_bias} \times S_{p\_oh}/\left(S_{p\_oh} + S_{PLCP}\right) \qquad \text{(II.7)}$$

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.

IV. SCENARIOS AND RESULTS

A. *Scenarios Description*

Two scenarios have been adopted in the work. Chain and Ring Scenario. Former one looks just like the one on **Figure II.2**, except that to the node 1 acts as a gateway and is connected with internet via cable interface. Each node transmits with the P_{tx}=200mW, so that transmission distance is slightly bigger than d_{n2n}. As a packet size value of 1500B has been adopted as it is said to be one of the most common packet sizes in the internet [11]. Usually the data rate is set to 54Mbps.

Nodes in the hexagonal network are laying on the corners of hexagons, what makes each node to have maximum of 3 One-Hop neighbors. Nodes are gathered in sets of the nodes, called rings that are in the same distance from the gateway in terms of hop counts. Rings are numbered with N_r as presented on Figure IV.1.

B. *Chain Scenario Results*

In following simulations the nodes use the same channel for simultaneous transmission often. The OPNET interference distance has been measured by means of simulations with the assumption of maximum Packet Error Ratio of 1%. The nodes were transmitting on the same channel and being continuously put further aside until R_{PER} drops below 1%. This happened for node to interferer distance d_{n2i}=1000m. Such a large range is because OPNET propagation model assumes freespace propagation, with no obstacles and clear LOS.

Typical application rate results are presented on **Figure IV.3**. The maximum application rate of One-Hop is maintained until $N_n = N_{ch}$. This allows each node to transmit on orthogonal channel and avoid interferences. This scenario, has topology as on Figure II.2 with the exception that node 1 is connected with internet via cable interface. As the traffic is 100% downlink the GW static radio interface is not used. Let M-R 3ch, 3 hops case be considered. In ideal channel assignment the node 1 is assigned channel Ch1, node 2 Ch2, node 3 Ch3 and node 4 Ch1. Because Ch1 is not used (100%DL case) there are no interferences, no losses and performance is as on Figure IV.4. Usually the channel assignment looks for example as follows node1 Ch1, node 2 Ch2, node 3 Ch3, node 4 Ch2. Because of 2 hops channel reuse distance the application rate drops to one presented on Figure IV.3. This assignment is because when UF evaluates two channels with the same value it chooses randomly one for assignment. If the UF was aware of the distance to the nodes that use the channels evaluated the same it could assign the further one resulting in decrease of interferences.

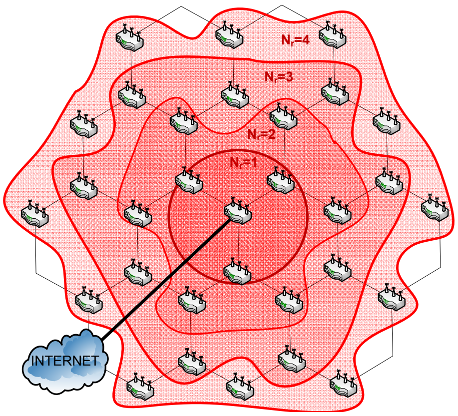

Figure IV.1 Hexagonal Topology.

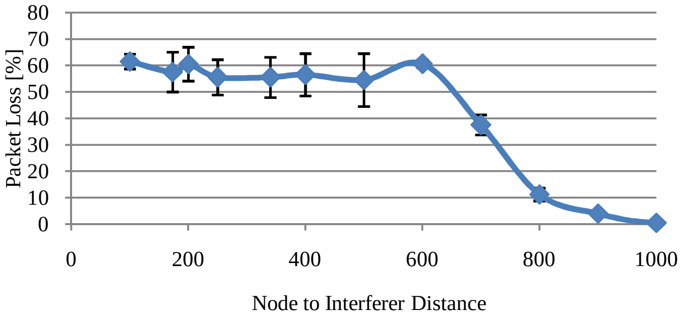

Figure IV.2 Interference Range Study.

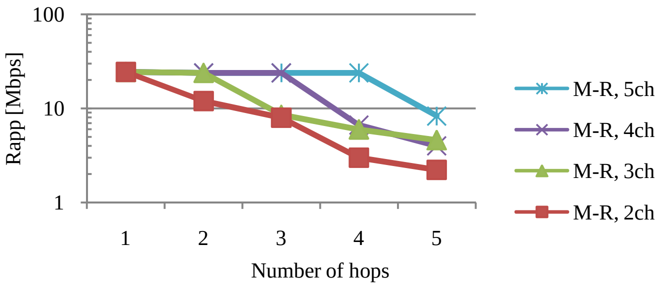

Figure IV.3 Application Rate Study in chain Scenario.

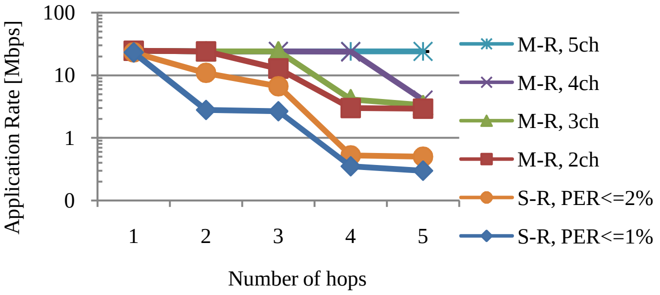

Figure IV.4 Application Rate Study in Chain Scenario- Ideal Assignment.

C. Ring Scenario Results

1) Transmission power

The impact of different transmission power on performance of the network has been evaluated. Each time the value of the power has been increased so that the d_{tx} was covering 1, 2, and 3 ring nodes each time, looking from central GW node. This implies that each time the area of successful RTS-CTS messages is increased as well. Each time 7 orthogonal channels has been used.

As it can be seen from Figure IV.5 this brings positive effect for 3 and 4 rings network. In 3 ring network nodes using the same channel in static interface are usually situated 2 hops away from each other. As the power increase from 200mW to 530mW increases the RTS-CTS reception distance to 2 hops away the increase in performance is present. Similar case is for 4 hops network, where increase of P_{tx} power to 1000mW increases RTS-CTS successful reception distance to 3 hops and that is where usually the same channels are reused.

As for first two analyzed transmission powers 4 ring network did not present satisfactory performance the study to investigate that is conducted. The all obligatory supported by 802.11a standard are investigated. Together with data rate decrease, $P_{min}(R)$and $P_{SINR_{min}}$ what allow to decrease the theoretical interference distance d_{i_t}. The values of P_{tx} are set so that the d_{tx}=109m is kept each time.

The parameters of study are presented in Table IV.1 and the results for 4 ring scenario in Table IV.2. As one can observe each time the performance is very poor, which is caused by collision due to simultaneous transmissions on the same channel. The main cause for this is average power decay set in Opnet to simulate freespace propagation.

2) Rts-cts evaluation

As next study the RTS-CTs evaluation has been run with various traffic characteristics. 2 Ring topology has been adopted with $N_{ch} = 11$, P_{tx} =200mW and data rate of 54Mbps.The traffic characteristics were: 100%DL, 100%UL, 25%UL/75%DL and 50%UL/50%DL traffic.

The results are presented on Figure IV.6. The CSMA/CA was developed to coordinate the radio transmissions of nodes competing to access the same channel. The proof for that can be seen from results as whenever the UL traffic is present RTS-CTS mechanism is showing better performance. In UL case a few nodes are competing to transmit to the same node. In 100%DL traffic in both cases the network reaches 100% of theoretical maximum (as there are 11channels and 10 nodes), but the case without RTS-CTS has got this maximum higher, because there is additional overhead connected with using this mechanism.

3) K_Neighbourhood

The next study is conducted over 3 Ring topology with $N_{ch} = 11$ and for 2 different traffic characteristics. The influence on performance of network of $K\_Neibhourhood$ parameter is studied. The results of achieved R_{app} are presented on Figure IV.7.

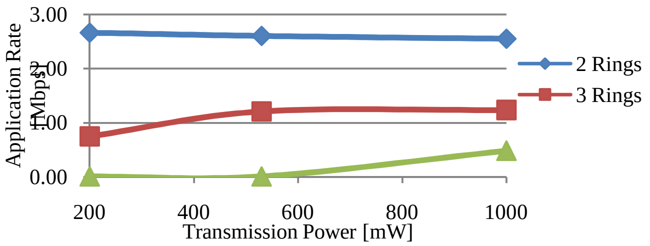

Figure IV.5 Application Rates for various topologies and transmission powers.

TABLE IV.1 PARAMETERS FOR DATA RATE STUDY.

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

TABLE IV.2 RESULTS FOR DATA RATE STUDY.

R	***Mbps***	**6**	**9**	**24**	**54**
d_{i_t}	***m***	794	1 112	1 778	5 623
R_{app}	***Kbps***	12	12	12	12
Packet Loss	***%***	13	13	13	10

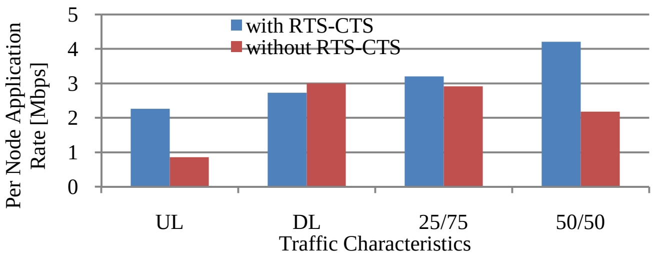

Figure IV.6 Performance in RTS-CTS evaluation.

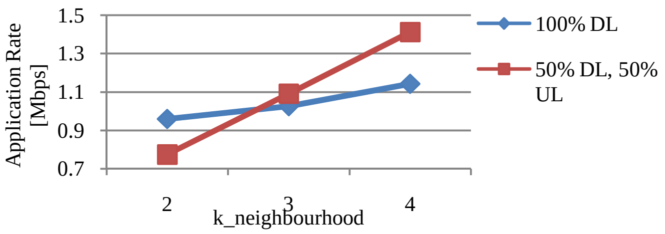

Figure IV.7 Performance in K_Neighbourhood evaluation.

The $K\_Neibhourhood$ parameter directly influences the number of nodes and the part of the network that the UF can evaluate when assigning the channels. It is clear that it leads to better performance as more channels are reused, what is presented in Table IV.3. When $K\_Neibhourhood$=2 3 of the channels are not used at all. This happens as UF assign the channels that are evaluated with the lowest usage randomly. If a few of them is not used at all inside the $K\_Neibhourhood$ area they are evaluated the same and a random one is picked up. This lead to not optimal radio resource management. As one can see from Table IV.3 the increase in $K\_Neibhourhood$ helps to spread channel usage to more nodes and relieve the GW channel.

The convergence time results are presented on Figure IV.8. The more nodes are taken into evaluation the longer the convergence time is as each change of static channel influences larger part of the network. This makes the information about it be spread longer as it must pass more hops. As the simulations in this work assume that no new nodes appear in the network during the simulations the convergence time is limited. If the new nodes were appearing, like it happens in ad-hoc networks the convergence of the network may become a problem.

4) Number of channels and UF in downlink

The next study is analyzing the influence of N_{ch} on the network. 3 Ring scenario is used, 100%DL characteristics, $K\_Neibhourhood$=4, data rate of 54Mbps and P_{tx}=200mW. The relative to R_{t_app} results of R_{app} are presented in Table IV.4, while non-relative on Figure IV.9.

As one can observe from the $N_{ch} = 7$ and above the usage of WLU presents higher value of application rate. The lower performance of WLU when utilizing $N_{ch} = 4$ is because strategy of protecting GW channel makes other nodes reuse the same channel too often as presented in Table IV.5, where 10 nodes receive on the same channel Ch2. When LU is used the maximum number of nodes fixed on the same channel is 5, which allow to achieve higher R_{app}.

Situation changes with increase to $N_{ch} = 7$, where maximum number of nodes using one channel is 5, and the nodes forwarding more traffic i.e. GW and 1st ring nodes have got separate channels assigned.

5) Number of channels and UF in uplink

The next study is configured in the same manner as before, with this exception that the traffic is 100%UL. The relative application rate results are presented in Table IV.7, while non-relative one on Figure IV.10.

In each case the WLU allow to achieve higher R_{app} for each user. Since all of the traffic is scheduled uplink, each time child nodes are competing to access the static radio interface of the same parent node. This is mainly when the strategy of "protecting" channels that forward more traffic proves to be most efficient. Even with $N_{ch} = 4$ the WLU is twice better than LU. When the $N_{ch} = 11$ both UF are starting to present the same performance, what means that for efficient radio resource management the WLU function is a better choice.

Table IV.3 CHANNEL USAGE IN K_NEIGHBOURHOOD STUDY.

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

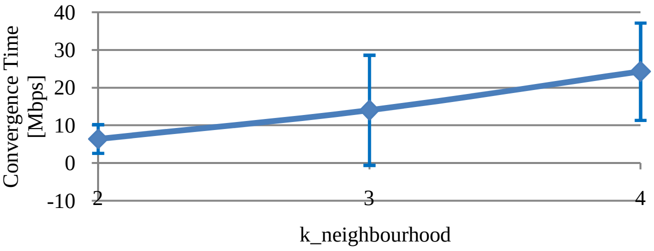

Figure IV.8 Convergence Times for various K_Neighbourhood.

TABLE IV.4 RELATIVE APPLICATION RATE IN DOWNLINK.

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

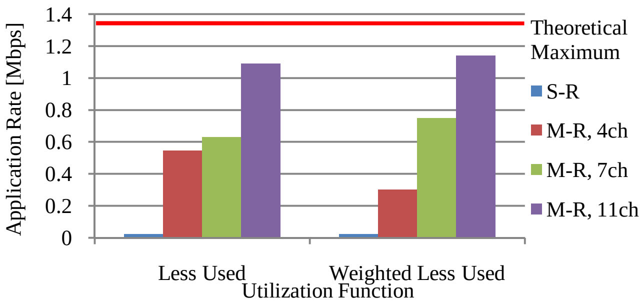

Figure IV.9 Non-relative Application Rate in Downlink.

TABLE IV.5 CHANNEL USAGE FOR NUMBER OF CHANNELS=4.

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

TABLE IV.6 CHANNEL USAGE FOR NUMBER OF CHANNELS=7

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

The results from delay studies are presented Figure IV.11. The more heavily the interface is loaded the higher the delays become. WLU presents higher delays as it must forward more traffic in the same amount of time as LU.

6) Traffic Characteristics

The next study is conducted using 3 Ring topology, 11channels, $K\_Neibhorhood$=4, data rate of 54Mbps and $P_{tx} = 200$mW. It compares the output of using two UFs with different traffic characteristics. The non relative results are presented on Figure IV.12 and relative ones in Figure IV.8.

Just like studied before, whenever UL traffic is present WLU shows better performance. The theoretical maximum for bidirectional cases is not marked on Figure IV.12 as it is twice larger than for unidirectional one.

The results showing delays from this study are presented on Figure IV.13. The delays are longer for WLU as it forwards more traffic. In 100%DL case the delay for LU is longer so it shows that even for DL case the channel assignment of WLU is better. One must be reminded that in DL case the channel of static interface of GW is not utilized at all, so N_{ch} drops from 11 to 10. Maintaining the same application rate proves WLU to be better choice than LU.

7) Active Nodes

As normally not every node generates the same traffic, number of active nodes N_{n_act} that are nodes generating traffic, is varied. To make the scenario realistic the traffic characteristics were set to 25%UL/75%DL. The $N_{ch} = 7$, $P_{tx} = 200$mW and both UFs are used in 3 Ring Scenario.

The results of R_{app} are presented on Figure IV.14. The network adjusts the application rates so that when not every node is transmitting the performance is better for each end user. The WLU for lesser number of nodes is performing better as each time on the paths from active nodes to the gateway the channel assigned are different. This happens more often than in LU UF because of different weights assigned to the nodes from different rings.

The delays from study are presented in Table IV.9. The delays for $N_{n\_act} \leq 2$ are higher than rest because of many possible options of channels assignment. As one can see however the WLU is more stable (lesser Std. Dev.). This is similar case as already explained in chain scenario results, where “ideal” and “non-ideal” channel assignment is presented.

TABLE IV.7 RELATIVE PERFORMANCE IN CHANNEL NUMBER IN UPLINK.

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

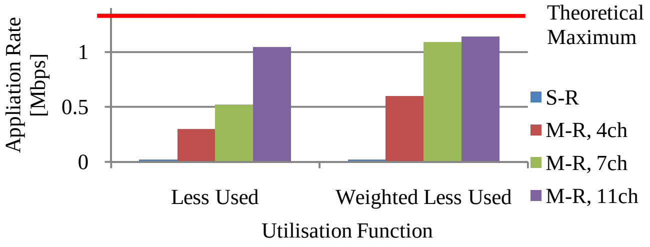

Figure IV.10 Non-relative performance in Uplink.

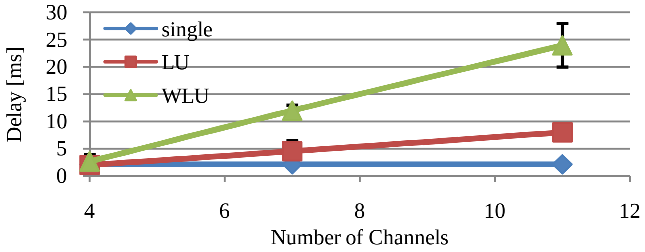

Figure IV.11 Delays in Uplink.

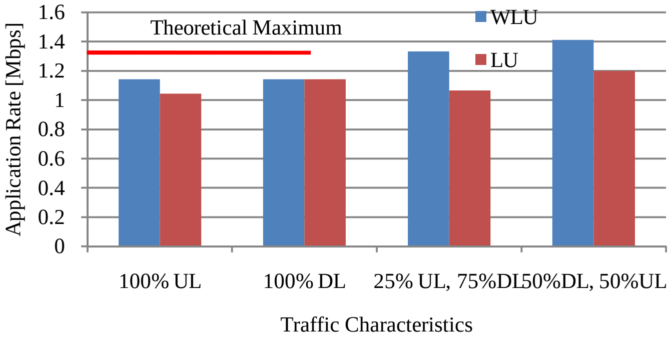

Figure IV.12 Non-relative performance for traffic Characteristics.

TABLE IV.8 RELATIVE PERFORMANCE IN TRAFFIC CHARACTERISTICS STUDY.

	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

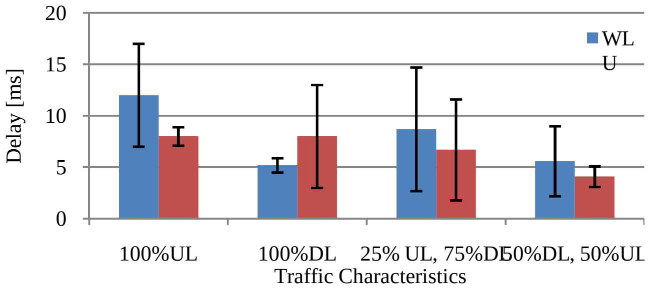

Figure IV.13 Delays in traffic characteristics Study.

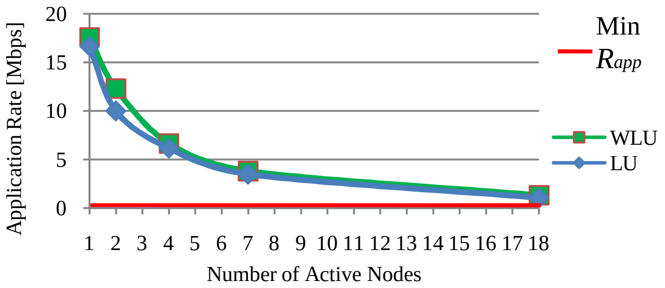

Figure IV.14 Performance in Active Nodes Study.

TABLE IV.9 AVERAGE DELAYS IN ACTIVE NODES STUDY.

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

The same study is conducted for 4 ring topology. Results are presented in Table V.1 for WLU and Table V.2 for LU. As for $N_{n\_act} > 4$ the performance is unacceptable the same offered application rate is set and only the delays are analyzed. Because of high OPNET interference ranges the 4 ring network can be used only with $N_{n\_act} \leq 4$ transmitting at the same time. This will keep the collision level on acceptable level allowing to reach connectivity.

As presented in two tables the cases on “ideal” and “non-ideal” channel assignment are also valid in this scenario. Which makes the WLU more reliable choice in terms of achieving higher application rates.

V. CONCLUSIONS

This work focuses on performance analysis of Wireless Mesh Network, implemented over 802.11a system. The influence of main network, nodes and utilization function parameters is evaluated in terms of achieved application rate, delays and packet loss. The goal was to find optimal configuration of a network to achieve maximum performance for end user.

The node model, together with RCA has been derived from [3]. The network is chain or ring topology. OPNET Wireless Suite 15.0A simulator has been used for simulations.

The first studies showed that interference range in Opnet, under the condition of $PER \leq 1\%$ is 1000m. This is because propagation model implemented in Opnet assumes freespace propagation. If one wishes to simulate rural or urban environment, one need to change the value of average power decay in Opnet from value of 2 to higher one (max. 4). Such a vast interference range influences the performance when any nodes in any scenario transmit over the same channel simultaneously.

In chain topology the maximum performance is reached when the $N_{ch} = N_n$ for worst channel assignment. When the assignment is ideal, the maximum performance is reached for $N_{ch} = N_n - 1$.

The first study of Ring topology is a P_{tx} study. For 2 Ring topology the best performance is achieved forP_{tx} =200mW, for 3 Ring topology the best one is forP_{tx} =530mW, while for 4 Ring topology the only possible to use value of $P_{tx} =$ 1000mW. Each time the performance increase is because of range increase of RTS-CTS messages successful reception area.

The comparison between CSMA/CA with and without RTS-CTS presented that whenever the traffic characteristics consists of Uplink traffic it is beneficial to use RTS-CTS coordinated access. In 100%UL case the R_{app}=2.26Mbps with RTS-CTS and 0.86Mbps without one. For 100%DL the performance is 2.72Mbps with RTS-CTS and 3.25Mbps without one.

When the performance was evaluated for K_Neighbourhood influence, it has been showed that the higher the parameter is the higher R_{app} is. The maximum values is 77.4% of theoretical maximum for 50%DL/50%UL case in 2 Ring scenario and 51.9% for 3Ring scenario in the same case.

TABLE V.1 STUDY RESULTS FOR ACTIVE NODES IN 4 RINGS.

	WLU				
	[%]		***[ms]***		***[Mbps]***
N_{n_active}	***loss***	***Std. Dev.***	τ_{max}	***Std. Dev.***	R_{app}
15	7.8	1.2	32.7	12	0.01
10	6.1	1.2	26.6	20	0.01
6	2.9	2.8	6.6	4.4	0.01
4	0.5	0.3	8.1	5.4	5.22
3	0.7	0.3	6.9	0.4	5.22
2	0.6	0.3	5.4	2	5.00
1 (non-ideal)	0.02	0.2	7.8	1	22.64
1 (ideal)	0.02	0.2	7.8	1	22.64

TABLE V.2 STUDY RESULTS FOR ACTIVE NODES IN 4 RINGS.

	LU				
	%		***ms***		***Mbps***
N_{n_active}	***loss***	***Std. Dev.***	τ_{max}	***Std. Dev.***	R_{app}
15	7.0	0.8	33.0	11	0.01
10	6.6	1.1	31.0	17	0.01
6	2.4	2.1	6.4	5	0.01
4	0.4	0.3	5.9	6.2	4.00
3	0.6	0.4	4.3	2.1	4.44
2	0.6	0.1	2.6	1.5	4.62
1 (non-ideal)	0.1	0.4	2.1	2.1	6.32
1 (ideal)	0.01	0.01	8.5	1.9	22.64

It has been showed in Number of Channels for Downlink study that for 3 ring network there is value of N_{ch}=7 above which the network performs better when using WLU. Below that value the performance is better for LU UF. For N_{ch}=7 the WLU reaches 55% of R_{t_app}, while for LU it is 46% of R_{t_app}. In Uplink case the WLU is performing better for each N_{ch} case.

In traffic characteristics case it has been showed that wherever the traffic consists of Uplink packets the performance is better when WLU is used. In the most loaded scenario of 50%DL/50%UL case the performance is 52% of R_{t_app}, for WLU while for LU it is 44%.

Simulations of various number of N_{n_act} have been conducted to check if 4 ring network is performing with lower load. It has been found that for P_{tx}=200mW the network manages to forward packets only for $N_{act} \leq 4$. Moreover for 1 active node it has been showed that it is beneficial to use WLU UF. While using LU the channel assigned to the nodes in path from active node to the GW often are overlapping, what results in collisions and performance ranging between [6.32Mbps, 22.64Mbps]. When WLU is used the performance for 1 active node is always 22.64Mbps.

Possible future work should take into consideration:

- Simulations with nodes dynamically connecting to the network,
- Modification to the link layer of a node, allowing the node to transmit over static interface each time it is not used for receiving,
- Adjustment of weights given to the nodes by WLU,
- Performance analysis of a network using various services and packet sizes,
- Modification to the link layer of a node allowing to prioritise the packets according to services.

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