Routing for capacity improvement in Multi-Channel-Width Multi-Radio Wireless Mesh Networks

Celso Barbosa Carvalho[1], José Ferreira de Rezende[2]

[1]Departamento de Eletrônica e Computação, Federal University of Amazonas
[2]LAND, Federal University of Rio de Janeiro, Brazil
ccarvalho_@ufam.edu.br, rezende@land.ufrj.br

***Abstract*:** This study indicates that the assignment of multiple channels with different bandwidths to links of a IEEE 802.11 wireless mesh network can drastically increase the capacity of these networks considering equal amount of available spectrum. However, this is possible only for networks where routers are equipped with multiple radios. In this context, this paper proposes a metric used to select the amount of radios and width of the channels to be used in each link, as well the routing path that enables a decrease in the interference between those links. We use simulations in ns-2 to assess the proposed routing metric and compare it with others in the literature. The obtained results point to an increase in the capacity of the studied networks.

***Keywords*:** Routing, Channel assignment, Wireless mesh networks, IEEE 802.11, Channel capacity**.**

1. Introduction

The great applicability of Wireless Mesh Networks (WMNs) makes important to increase the maximum end-to-end throughput of the routes used by their flows, also known as network capacity (bits/s) [1].

In order to increase the throughput of WMNs, most researches related to routing metrics [2], consider the use of fixed width communication channels (e.g. 20 MHz for IEEE 802.11 technology); however, researches reveal that the performance of wireless networks can be improved by employing communication channels of different widths (e.g. 5, 10 e 20MHz) [3].

The application of smaller width channels (e.g. 5MHz) enables an increase in the network capacity facing a large number of links competing for the spectrum. Firstly, the division of the spectrum into a higher amount of orthogonal channels decreases link contention; secondly, the spectral network efficiency increases by using parallel transmissions with smaller width channels. As an example, we have four (04) channels of 5MHz able to carry out a parallel and shorter transmission time of four (04) frames when compared with a single channel of 20MHz; both transmissions occupying a total bandwidth of 20MHz. In the case of the 20 MHz channel width, serially; it´s spent four (04) times the MAC-layer waiting times (e.g. congestion window and Inter Frame Spaces) in the transmission, which increases the total transmission time. In contrast, when the amount of links competing for the spectrum is small and if routers have few number of transmission radios, the use of larger width channels generates the most satisfactory spectral efficiency [4] due to the higher capacity of these channels [5]. Another advantage of links established in smaller width channels is their longer transmission range. The transmission range of a link depends on the minimum power required for the receiver to decode the transmitted signal. This power, called minimum sensitivity (S), is directly proportional to the channel width; therefore, the lower width a channel has, lower is the value of S, and, consequently, longer is the transmission range [3, 4].

Chandra et.al [3] carried out experiments demonstrating the effects of using channels of different widths on the throughput and range of transmitted signals. In the paper, the authors develop an adaptation algorithm establishing the channel modulation and width of a link with node equipped with one transmission radio.

Yuan et.al [5] developed a MAC (Medium Access Control) protocol and algorithm able to adapt to the channel width, frequency and transmission time of Cognitive Radios (CRs). The CRs are equipped with two (02) radios, one to locate the white spaces and the other for transmission. In this context, the authors propose modifications in the 802.11 MAC to generate the messages of the proposed protocol.

Carvalho and De Rezende [4] proposed a metric that generates values used to execute routing, establish the amount of radios and channel width applied to the links of a WMN; however, the amount of radios is established statically and routing metrics values do not account for interferences.

In this paper, we work with WMNs scenarios with routers able to adapt communication channel width; therefore, we propose a metric implemented in the network layer in order to increase the end-to-end capacity of routes, and consequently increase the network capacity. Metric values are used to establish the routing flows; conduct channel assignment, select the width of each channel and choose, due to the existing interference, the amount of transmission radios used in each link. According to the bibliographical research, this paper is pioneer at proposing a metric with values employed to perform all of those tasks. To assess the proposition and compare it with other metrics in the literature, we employ simulations in the NS-2 with the physical interference model as in [6, 7, 8, 9].

The paper presents the research divided in the following sections: Section 2 – related studies; Section 3 – the proposed routing metric and mechanisms used to determine routes of greater capacity; Section 4 – simulation environment and settings which describes the methodology employed to simulate channels with different widths in NS-

2; Section 5 – assessment of proposed metric with results compared with other studies in the literature; Section 6 – conclusions and future work.

2. Related Studies

ETX metric (Expected Transmission Count) [2] uses measures of frame delivery rates in the direct df and reverse dr link. Equation ETX = 1/(df × dr) represents the amount of transmissions required for the data frame of a link $e_{i,j}$ to be received in j, and the ACK frame to be received in i.
The objective of ETT metrics (Expected Transmission Time) [10] is to estimate the total time, including retransmissions, required to transmit and acknowledge a frame in a link. In equation $ETT = ETX \times \frac{S}{B}$, ETT is the metric value for a link $e_{i,j}$, ETX is the value of ETX metric for the same link, S and B represent, respectively, the frame size and frames transmission rate.
The value of WCETT (Weighted Cumulative Expected Transmission Time) metric [10] is determined for a route p, according to equation $WCETT = (1-\beta) \times \sum_{i=1}^{n} ETT_i + \beta \times \max 1 \leq j \leq kXj$. Term $i=1nETTi$ represents the sum of the ETTs of the links in the route; term $\max_{1\leq j\leq k} X_j$ returns the sum of links transmission time of the route, in the channel j with higher occupation time. Variable β is a parameter with value in the interval $1 \leq j \leq \beta$, where β with value close to one (01) favors the choice of higher capacity routes and β with value close to zero (0) establishes the choice of lower delay routes.
MIC metric [11] determines values for a path p according to equation $MIC = \frac{1}{N\,x\,\min\ ETT} \sum_{link\ l\ in\ p} IRU_l + node\ i\ in\ pCSCi$. In this equation, N is the number of routers in the network and $\min(ETT)$ is the lowest ETT value among network links. There are also more two terms. The first term is called IRU (Interference-aware Resource Usage) with values calculated by $IRU = ETT_l \times N_l$, where ETT_l is the ETT of a link l that is part of path p and, N_l is the number of routers that are neighbors of link l and, that are interfered by the transmissions of link l. CSC (Channel Switching Cost) is the second term of MIC metrics with values given in Equations (1), (2) and (3).

$CSC_i = w1 \quad if\ CH(prev(X)) = CH(X)$ (1)
$CSC_i = w2 \quad if\ CH(prev(X)) = CH(X)$ (2)
$0 \leq w1 \leq w2$ (3)

In these equations, variable CSC_i represents the channel $CH(X)$ assigned for transmission of router i and, $CH(prev(X))$ represents the channel chosen by the router that is previous than i in the route. Variables $w2 > w1$ captures inter-flow interference, assigning greater weight values if the channel chosen by router i is the same channel chosen by the previous router than i in the route.
In [12] equation $EETT_l = \sum_{link\ i\ \epsilon\ IS(l)} ETT_i$ calculates the EETT metrics (Exclusive Expected Transmission Time). $EETT_l$ of a link l is the result of the sum of ETT_i of each link i in the Interference Set $IS(l)$ of link l; where $IS(l)$ includes link l itself. The sum of $EETTs$ of the route links gives the metric value of a route.

B-MTM metrics (Burst per Medium Time Metric) [4] has values given through the inverse of the sum of the capacities of all link e that belongs to a physical link pe. Being a physical link pe a set formed by one or more individual links e established between nodes (i,j) in channels of width ω. The metric values are given in equation $B-MTM_{pe} = 1/(qR_{pe} x\ Cap_e)$, where qR_{pe} is the amount of radios used in a physical link pe and $Cap_e = (8\,x\,L_{MPDU})/t$ is the calculated theoretic capacity of all links that belongs to the physical link pe. Where L_{MPDU} and t are the average size and the transmission time of a MAC Protocol Data Unit, respectively.

2.1 Comments regarding the existing routing metrics

All routing metrics cited in this section could work in a Multi-Channel Multi-Radio (MCMR) WMN. However, with the exception of BMTM metric, no other uses in its calculations the amount of radios and channels with which a router can establish links with its neighbors. In this case, these metrics cannot be used to establish a link with multiple radios and channels as the scenario (I) of Figure 1. In this scenario, there are two channels (c1 and c2) and the router A uses its two radios to establish a link to communicate with router B. In this case, we find that the existing metrics are not able to take advantage of all the Available Spectrum (AS), despite the existence of radios that can be used for this. Scenario (II) of Figure 1 shows how is the channel assignment in MCMR environment for the routing metrics of the literature. Router A may only establish links using multiple radios on different channels; each link is established with different routers (routers B and C).

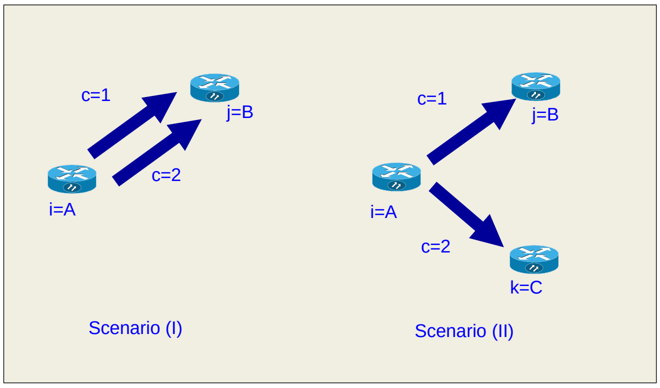

Figure 1. Link establishment with multiple radios

Regarding to the B-MTM [4] metric, despite it can establish one link using multiple radios; its problem is the lack of dynamicity. To determine values, this metric uses statically the maximum amount of radios that a router has to establish a link. Thus, this metric could be used to create the scenario I of Figure 1, where is used 2 radios to establish link AB. However, in this same scenario, if it is necessary to establish a new link between an other pair of routers (e.g. C and D) that interferes with link AB; the B-MTM metric would not generate values that represent the interference between links and would be used to establish both links AB and CD using the same 2 radios in the same two channels (c1 and c2). This would cause contention between the links AB and CD.

3. Determining routes and channels for capacity increasing

The following subsections explain the mechanisms and proposed metric.

3.1 Division and use of the Available Spectrum (AS)

According to [17], a node pair i,j can establish an individual link $e_{i,j,c^{\omega}}$ in a channel c_{ω} of width ω. A physical link $pe_{i,j,c^{\omega}}$, or just pe, is the set formed by one or more individual links e established between nodes (i,j) in channels of width ω. In this paper we call physical channel pc^{ω} a set of channels of width ω through which a physical link is established. To establish a physical link through multiple channels, it is required that a node pair (i,j) has and provides multiple radios to communicate to one another. As an example of applying physical links and physical channels, we shall consider a case in which the Available Spectrum $AS = 20MHz$ and a pair of nodes (e.g. A and B) that have each, two radios communicating in channels of $10MHz$ width. If the node pair AB verifies that there is no interference, it would use their two (02) radios to establish a physical link that uses two orthogonal channels of $10MHz$. In this case, the AS would form just one physical channel $PC^{\omega} = \{pc^{\omega} = 1^{10}\}$ composed of two (02) individual channels c^{ω} of $10MHz$ width (e.g. $pc^{\omega} = 1^{10} = \{c^{\omega} = 1^{10}, c^{\omega} = 2^{10}\}$. In a second moment, routers C and D establish a link that interferes with link AB. In this case, the routers of both links AB and CD to avoid interflow interference would use just one (01) radio to establish a link through one channel with its neighbor. With this decision each pair of routers would divide the AS in 02 physical channels forming the set $PC^{\omega} = \{pc^{\omega} = 1^{10}, pc^{\omega} = 2^{10}\}$ and being each physical channel composed of just one individual channel c^{ω} of $10MHz$ width (e.g. $pc^{\omega} = 1^{10} = \{c^{\omega} = 1^{10}\}$ and $pc^{\omega} = 2^{10} = \{c^{\omega} = 2^{10}\}$). In this case the pairs AB and CD establish their links over the existing and non-interfering physical channels $pc^{\omega} = 1^{10}$ and $pc^{\omega} = 2^{10}$, respectively.

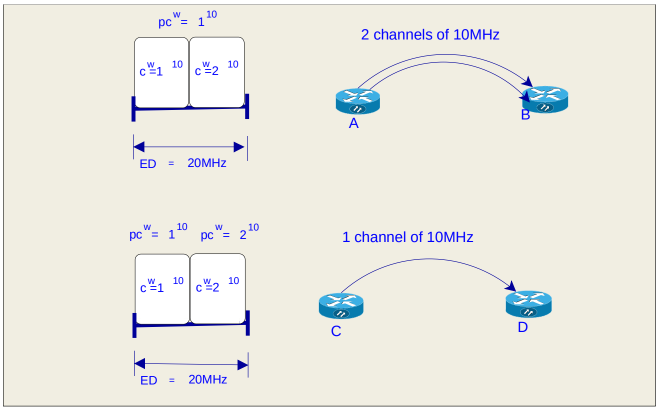

Figure 2. Spectrum division into physical (group of channels) and individual channels

3.2 MCWMR-BEETT Metric

The proposed metric is called MCWMR-BEETT (Multi-Channel-Width Multi-Radio Bits per EETT) is able to choose the amount of radios and width of channels used in each link and perform routing in order to decrease interference between links. As the B-MTM metric [4], the MCWMR-BEETT metric considers to determine its values the existence of multiple radios transmitting on a single link and the existence of different communication channel widths. Similarly, the MCWMR-BEETT metric aims to increase the capacity of the network routes. Unlike B-MTM, the MCWMR-BEETT extends EETT metric and therefore considers both intra and inter-flow interferences. Another difference between the B-MTM and MCWMR-BEETT refers to the number of radios used for transmission in a link. In MCWMR-BEETT proposal, and unlike the B-MTM [4], this amount of radios can vary depending on the number of other links that interfere with the link to which is being calculated the metric value.

Equation (4) presents the calculations to obtain the values of MCWMR-BEETT (Multi-Channel-Width Multi-Radio Bits per EETT) metric, also called just BEETT. It is a multi-objective metric composed of the product of three variables α, δ and γ, with minimum value of 1.0; the lower its value the better the result.

$$MCWMR - BEETT = \alpha \cdot \delta \cdot \gamma \quad (4)$$

$$\alpha = \frac{Cap_{opt}}{Cap_{ef}} = \frac{\frac{qR_{pe} \cdot L_{data} \cdot 8}{T}}{\sum_{e \in pe} Cap_e} = \frac{\frac{qR_{pe} \cdot L_{data} \cdot 8}{T}}{\sum_{e \in pe} \frac{8 \cdot L_{data}}{EETT_e}} \quad (5)$$

$$\delta = \max\left(\frac{|\mathrm{IS(pe)}|}{|\mathrm{PC}^{\omega}|}, 1\right) \quad (6)$$

$$\gamma = \max\left(\frac{AS}{OS}, 1\right) = \max\left(\frac{AE}{|IS(pe)| \cdot qR_{pe} \cdot \omega}, 1\right) \quad (7)$$

The objective of variable α in Equation (4) is to choose physical links with higher capacity; it is given by the ratio between the theoretical value of capacity Cap_{opt} and the effective capacity Cap_{ef} for a physical link pe. In Equation (5), qR_{pe} represents the amount of radios used in the physical link pe, L_{data} is the frame size in bytes, and T is the sum of the data and acknowledgement transmission times of a link, also showed in Equation (9) of Section 4.1, and which depends of the modulation and channel width $\omega \in \{5, 10, 20MHz\}$. The effective capacity of the physical link Cap_{ef} is given by the sum of capacities Cap_e of individual links that are part of physical link pe. Cap_e is determined in Equation (5), where variable $EETT_e$ is the value measured for EETT metric for all link $e \in pe$.

Term δ in Equations (4) and (6) is a ratio between the amount of physical links interfering in the physical link pe, represented by the Interference Set $|IS(pe)|$ and the amount of existing physical channels, given by the set $|PC^{\omega}|$, obtained through the division of the available spectrum AS into a set $|PC^{\omega}|$ of physical channels. The objective of this ratio is to choose physical links with lower amount of other interfering physical links. The lower value of term δ is one (01) and indicates that a link has at least itself as interferer.

Finally, term γ in Equations (4) and (7) represents the ratio between the available spectrum AS and the Occupied Spectrum OS; in the case all of the physical links that are part of the set $IS(pe)$, decide to employ physical links with the same characteristics as pe (e.g. channel width). In Equation (7), $|\mathrm{IS(pe)}|$ is the amount of physical links of the Interference Set $\mathrm{IS(pe)}$, qR_{pe} is the amount of radios used in the physical link pe and, ω is the channel width employed in this physical link. Value 1, within function max represents that the AS is fully occupied.

At this time we comment on the calculation of term δ of Equation (6). For simulations, it was developed a centralized simulation script in which we used Dijkstra's algorithm to determine the routes in the network. Established routes are stored in tables. These tables were used to check the amount of physical links $|IS(pe)|$ that are established in channels with spectrum that overlaps the physical link to which we want to calculate the metrics' value.

Another comment is about the determination of $EETT_e$ variable of Equation (5). As presented in Section 2, the metric value of a link e is given by the sum of ETTs of all links that are part of $IS(e)$, this set formed by the interfering links of e. Thus, the $EETT_e$ value of Equation 5 is given by $EETT_e = \sum_{link\ e2\ \epsilon\ IS\ (e)} ETT_{e2}$. In the latter equation, variable $EETT_e$ represents the EETT value for a individual link $e_{i,j,c^{\omega}}$. In the same equation, variable ETT_{e2} represents the ETT value for every individual link $e2$ that is part of the Interference Set of link e.

3.3 Establishing Routes

In Equation (8), we used BEETT_{pe} to represent the value of the proposed metric for a physical link pe, and BEETT_{Ro} to represent the value of the metric for a route Ro.

$$BEETT_{Ro} = (1-\beta) \times \sum_{pe\ \epsilon\ Ro} BEETT_{pe} + \beta \times \max_{pe\ \epsilon\ Ro} BEETT_{pe} \quad (8)$$

As in WCETT metric, β is an adjustable parameter with values between zero (0) and one (01). For the assessment of MCWMR-BEETT metric, β assumes value 0.5. Term $\sum_{pe\ \epsilon\ Ro} BEETT_{pe}$ represents the sum of the metric values for all of the physical links pe of the route Ro. Term $\max_{pe\ \epsilon\ Ro} BEETT_{pe}$ represents the greater metric value among the links of route Ro. The former term of Equation (8) functions to decrease the number of hops in the route since the higher the number of hops the higher the product $time \times frequency$ consumed by the links of the route, and consequently the higher the product $time \times frequency$ denied to other links. The latter term of Equation (8), functions to establish the choice of higher capacity links.

To establish the metric value of a route, we developed a modified version of the Dijkstra's [18] algorithm receiving a metric matrix of size $|V| \times |V| \times |PC|$. Therefore, before establishing a route, it is required to determine the size of the dimension $|PC|$ of the metric matrix, where PC is the set of physical channels that is given by $PC = \bigcup_{\omega}^{W} PC^{\omega}$. We established the set of physical channels $|PC|$ of width ω according to aforementioned as described in Section 3.1.

4. Simulation environment and settings

This section presents the model incorporated to the NS-2 to simulate different channel widths and the effects of this modeling on transmission time, throughput and capacity and, transmission range of a link.

4.1 Channels of Different Widths and Effects on Links Transmission Time

To implement the effects of using different channel widths on link's transmission time, we used the NS-2.33 with support to multiple channels and multiple radios (MCMR) proposed in [13]. By using the MCMR model, it is possible to simulate, for instance, the scenario of a link established through one or more communication channels. With MCMR model, each wireless node has one instance of the application, transport and network layers and, one or more instances of link and physical layers, where each physical layer is associated with an orthogonal channel.

In addition, we used and implemented modifications to MAC 802.11g [14] and agent NOAH [15]. The latter received a staggering scheme, where in a transmitter node each segment received from the transport layer is forwarded, cyclically by the network layer, to one of the stages of the link layer.

In the case of MAC 802.11g [14], we implemented modifications to represent the differences in the transmission time of frames transmitted in channels of different widths (e.g. 5, 10 and 20MHz) and with different modulations (e.g. used to offer data rates of 54, 48, 36, 24, 18, 12, 9 and 6Mbps) of OFDM physical layer IEEE 802.11. These differences in the transmission time of frames reflect on differences of links capacity. Variables of Equations (9) to (13), except β [3], appear codified in the extension of [14] in order to represent the total transmission time T and the acknowledgment time of a MPDU (MAC Protocol Data Unit) of IEEE 802.11g OFDM physical layer; variable β of Equations (12) and (13) is a parameter with value given by $\beta = 20MHz/\omega$, where $\omega \in \{5, 10, 20MHz\}$ is the communication channel width. We observe in the establishment of β, as the channel width ω decreases, the values of the data and the acknowledgment transmission times (t_{DATA} and t_{ACK}) of MAC 802.11, respectively, increase. We introduce parameter β and modify MAC 802.11g of [11] in order to represent transmission time and acknowledgment time of a frame according to the channel width. Other variables and constants of Equations (9) to (13) are as follows: t_{CW}, in Equation (9), is the contention window time; $t_{SLOT} = 20\mu s$ of Equation (10) is a slot time; t_{DIFS}, in Equation (11), is the waiting time of a Distributed Inter-Frame Space; $t_{SIFS} = 10\mu s$ is the time of a Short Inter-Frame Space; t_{DATA} and t_{ACK} represent the transmission time of a data frame and of an ACK frame, detailed in Equations (12) and (13). In these last two equations, $t_{pr} = 20\mu s$, $t_{sym} = 20\mu s$ and the value 22 are related to the physical layer of OFDM representing, respectively, the MPDU preamble transmission time, the OFDM symbol transmission time and, the sum of bits in service field (for further applications) and tail field (end-of-frame delimiter). Also in these equations, R is the transmission rate generated by using modulation mR (e.g. modulation $m54$ has $R = 54$), 6μs is the value of time named Signal Extension with the function of including additional processing time to the demodulator. For variable R of Equation (13) value 6 is always assumed, since the ACK frame is always transmitted in IEEE 802.11 basic rate. In Equation (12) $L_{MAC} = 34bytes$ and L_{DATA} (variable size) represent, respectively, the size of the MAC header and data frame of MAC-layer. In Equation (13) $L_{ACK} = 14bytes$ represents the size of an ACK frame.

$$T = t_{cw} + t_{DIFS} + t_{DATA} + t_{SIFS} + t_{ACK} \quad (9)$$

$$t_{CW} = 8 \times t_{slot} \quad (10)$$

$$t_{DIFS} = 2 \times t_{slot} + t_{SIFS} \quad (11)$$

$$t_{DATA} = \beta \left[t_{pr} + t_{sym} \left(\frac{22 + 8(L_{MAC} + L_{DATA})}{4R} \right) \right] + 6\mu s \quad (12)$$

$$t_{ACK} = \beta \cdot \left[t_{pr} + t_{sym} \cdot \left(\frac{22 + 8 \cdot L_{ACK}}{4R} \right) \right] + 6\mu s \quad (13)$$

We summarize this section commenting that the modifications in width of a wireless channel changes the values of variables t_{pr} e t_{sym}, which account for the transmission time T (Equation 4) of an MPDU and the ACK frames in the wireless channel. This change in the values of the two variables is represented in Equations (12) and (13) through the use of variable $\beta = 20MHz/\omega$, with $\omega \in \{5, 10, 20MHz\}$. In this equation we can note that by reducing the channel width, the higher is the transmission time of an ACK and MPDU frame.

4.2 Channels of Different Widths and Effects on Links Throughput and Capacity

We used the NS-2 with the abovementioned configurations in frame transmission times that depend on channel width to simulate the scenario of Figure 3 where Router A transmits frames to router B, using 01 or more orthogonal channels $c = (1, \dots, |C|)$ of width $\omega \in \{5, 10, 20MHz\}$. Each router is equipped with $|C| = qR$ radios attached each one to a channel and, has the same number $|C| = qR$ of instances of the physical layer and data link layer protocols. In each of the routers there is only one instance of the application, transport (e.g. UDP) and network (e.g. IP) layer protocols. In a transmitter router, the messages generated in the application layer are passed to the transport layer, and then to the network layer that cyclically multiplexes datagrams to each of the protocol stacks below that include each one, an instance of the link and physical layer protocols.

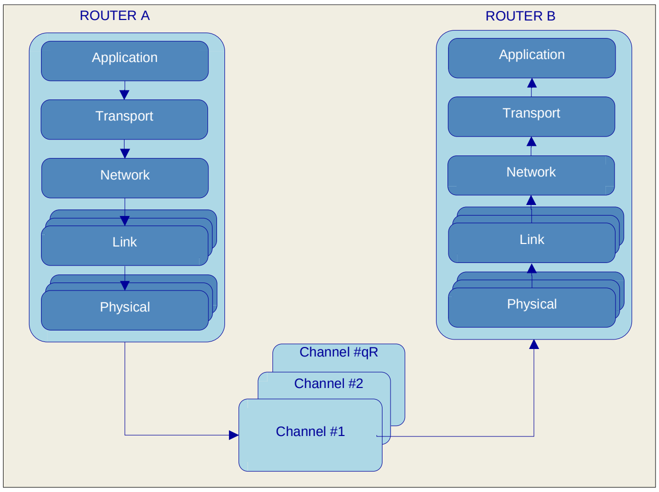

Figure 3. Routers transmitting in multiple orthogonal channels.

We fixed in m54 the modulation (used to offer data rate of 54Mbps) applied to the data frame transmission and in m6 the modulation used to transmit ACK frames; the value of the simulation time was 400s. In this scenario, we varied a CBR (Constant Bit Rate) source rate from one (01) to 40Mbits/s, in order to observe the behavior of the average throughput and capacity of a link by using 1, 2 or 4 channels of 20, 10 or 5MHz, respectively. In each of the three configurations for the amounts of simulated channels and channel widths, the value of the Occupied Spectrum (OS) is always 20MHz. We simulated two configurations of the described scenario with results presented in Figures 4 and 5. In the first configuration, node A uses a CBR source, while in the second configuration uses a source that generates messages with interval given by an exponential variable. For both types of source, the size of the messages is 2000 bytes.

In Figure 4, we observe that 20, 10 and 5 MHz channel width reach their capacity values when the CBR source rate is around 22, 28 and 35 $Mbits/s$. In Figure 5, we observe similar behavior, with more softened curves and the capacity of 20, 10 and 5 MHz channels reached their values around 20, 30 and 35$Mbps$ for the exponential source rate. These results corroborate the findings of [4], which stated that for a same value of occupied spectrum, a set of smaller width channels has higher capacity than larger width channels in IEEE 802.11g. In both figures, we observed that before the channels of width 5, 10 or 20 MHz reached their capacities, the throughput value is the same for all of the channels; therefore, the three (03) curves are coincident.

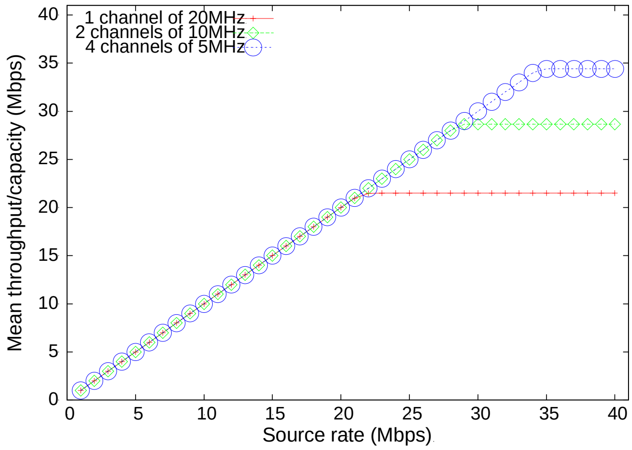

Figure 4. Throughput and capacity of 1, 2 and 4 orthogonal channels of 20, 10 and 5MHz. (CBR source)

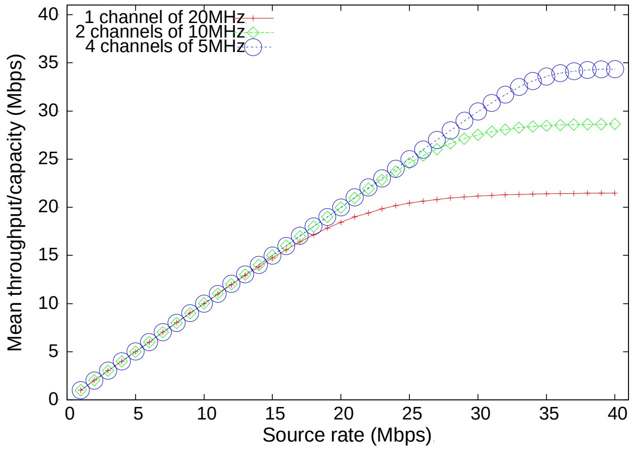

Figure 5. Throughput and capacity of 1, 2 and 4 orthogonal channels of 20, 10 and 5MHz. (Exponential source)

4.3 Channels of Different Widths and Effects on Receiver Sensitivity

Figure 6 illustrates the sum of the Receiver Noise Floor (RNF) and the SNR (Signal to Noise Ratio) to determine the value of minimum sensitivity of a receiver radio for a given modulation. Variable RTN (Receiver Thermal Noise) represents noise degree that is directly proportional to the products of Boltzmann constant $K = 1.38 \times 10^{-23} J/K$, absolute temperature $T_0 = 290k$ and communication channel width ω. Thus, the lower the value of ω the lower the value of RTN. The following noise degree in the figure is represented by variable RNF (Receiver Noise Floor), in (dBm), is given by the sum of RTN and Noise Fıgure (NF), that represents noises internally generated by the receiver circuit. The value of minimum sensitivity is given by the sum of RNF and the threshold of the Signal to Noise Ratio (SNR) required to decode a signal in a certain modulation. In Figure 6, we observe that lower the value of the channel width the lower the value of sensitivity, or value of power required to decode a signal in a certain modulation leading to the possibility of higher distance between transmitter and receiver in a wireless link [3].

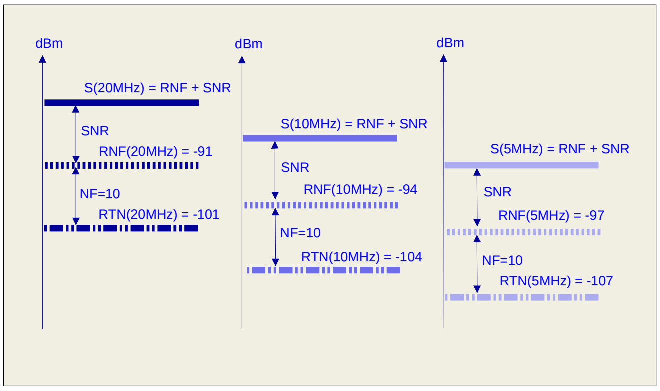

Figure 6. Minimum receiver sensitivities for channel widths of 5, 10 and 20MHz

For the simulations, we used the physical interference model [6,7,8,9]. This model uses Inequality (14), to establish that the reception probability of frames in a link $e_{i,j}$ is one, in case of the SINR (Signal to Interference plus Noise Ratio) between the reception power of the link frames ($Pr_{(i,j)}$ in Watts) and the sum of the power of frames from other interfering routers k ($Pr_{(k,j)}$ in W), at receiver j, exceeds or matches the $SINR_{th}$. In Inequality (14), the value of variable $RNF_w = 10^{(RNF-30)/10}$, given in Watts, represents the value of background noise perceived by the receiver.

$$\frac{Pr_{(i,j)}}{\sum_{k \neq i} Pr_{(k,j)} + RNF_w} \geq SINR_{th} \qquad (14)$$

During the simulations, we also used the rate control mechanism RA-SINR of the extension called DEI-80211MR of [14], a mechanism that transmits frames in a link, measures the value of SINR of the received frames and compares the values of SINR and $SINR_{th}$ required to receive a frame in a given modulation. Due to this comparison, the mechanism establishes automatically the transmission rate with higher data delivery rate of IEEE 802.11g (e.g. m6, … , m54). Another feature of the extension DEC-80211MR [11], allows configuring background noise perceived by each receiver router. Therefore to simulate different transmission ranges according to the channel width, this feature is used to set the value of variable RNF of each router. Thus, by using the channel widths of 20, 10 or 5 MHz, a router is configured, respectively, with the RNF values presented in Figure 6.

Simulations used the scenario with a link AB, where router A remains fixed at the point (0.0) of the Cartesian plane. Router B is movable, with initial positioning at point (5.0); every $30s$, B moves $5m$, finishing its trajectory at point (500.0). Router A transmits frames to B using a CBR source with rate 10Mbits/s and both routers have a single communication radio. By using the pattern of positioning described and the propagation loss of type log-distance [16] with propagation loss exponent $n = 2.86$, we carried out one simulation for 5, 10 and $20MHz$ channel widths.

Figure 7 indicates that as the distance between A and B increases, the transmission rate in the link for any of the simulated channel widths decreases. The figure also illustrates that for a given value of distance between A and B, the use of a narrow width channel involves the application of modulation in the link able to transfer higher amount of bits per symbol (e.g. modulation $m24$ transfers higher amount of bits per symbol than modulation $m18$) compared with wider channels. We observe such example at $75m$ of distance; by using, respectively, widths 20, 10 and 5MHz, the link uses modulations m24, m36 and m48.

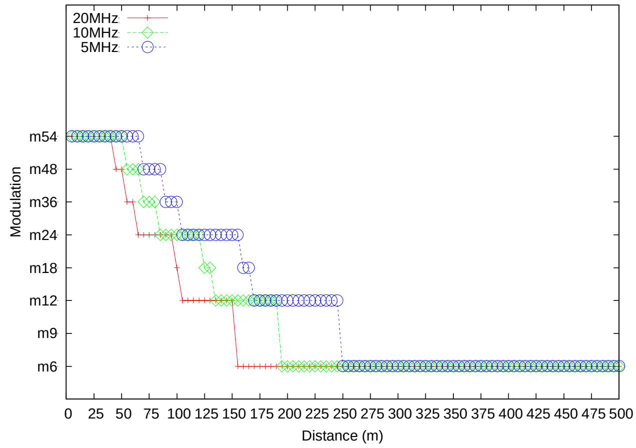

Figure 7. Distance x Modulation

5. Performance assessment

We used the NS-2.33, equipped with agent NOAH [13] with extensions MCMR [14] and 802.11g [15]; in addition, we added the following functionalities to the simulator.

- Routing through multiple radios and channels and cyclic frame transmission in a physical link pe established through multiple radios and channels;
- Transmission time of frames dependent on channel width;
- Interference between channels with overlapped spectrum. For example, a $AS = 40MHz$ can be divided by one node in two channels $c1^{20}$and $c2^{20}$of width $20MHz$ and four (04) channels $c1^{10}, c2^{10}, c3^{10}$ and $c4^{10}$ of $10MHz$. In this case, channel $c1^{20}$ has overlapped spectrum to channels $c1^{10}$ and $c2^{10}$;
- Minimum sensitivity dependent on the channel width used by the receiver radio;
- Routing metrics ETX, ETT, WCETT, EETT, B-MTM, MIC and MCWMR-BEETT.

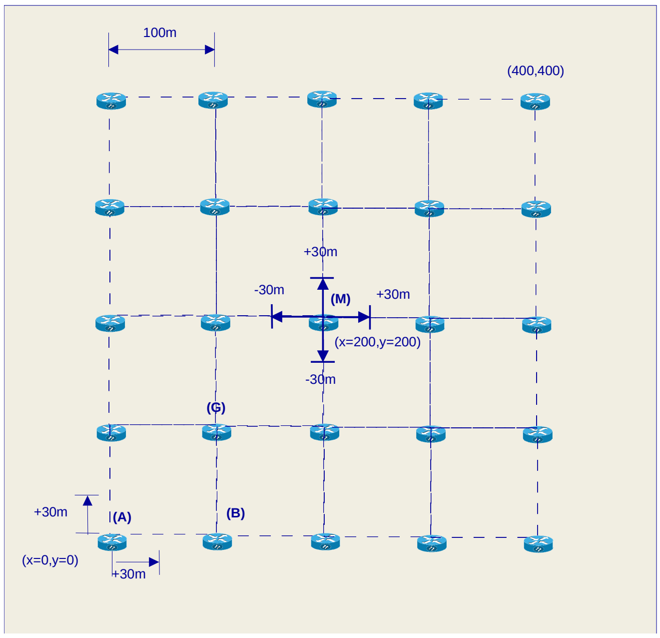

Figure 8. Simulation scenario

The assessment considered the scenario in Figure 8 of a 5×5 grid with line spacing of $100m$ and 25 nodes. Each simulation round had the nodes varying in $\pm 30m$, for both X and Y-axes, their positioning in relation to the intersection of rows and columns. Nodes do not exceed the border of the scenario with coordinates 0 and 400, in both X and Y-axis. Positioning variation of $\pm 30m$ enables the existence of minimum $d_{min} = 40m$ (e.g. nodes A and B) and maximum $d_{max} = 226m$ (e.g. nodes G and M) distances of separation between one hop neighbors. According to illustration in Figure 7, these values of distance enable the modulation used in a link to vary from $m54$ up to $m6$ for any of the simulated channel widths. The objective of this grid scenario is to simulate the disposal of routers in a campus wireless mesh network; the variation of positioning, in turn, is to simulate the node positioning due to the existence of obstacles.

$AS = 60MHz$ and parameter $E_{MAX} = 20MHz$ was used to establish the maximum spectrum value that a physical link is able to occupy. Each router was equipped with four (04) communication radios and one (01) additional radio to perform measures and transmit probes in channels of different widths. During the simulations, we admitted $k = \{1,3,5,7,9\}$ demands that, generated messages of size 1000 bytes, between distinct pairs of routers. The simulations lasted 220s and each new demand was admitted every 12s; therefore, in the configuration where is simulated nine (09) traffic demands, the last one was admitted at $12s \times 9 = 108s$. For each new accepted demand, we performed the Dijkstra's algorithm to establish the new route. At simulation time $120s$ and $220s$, we initiated and completed, respectively, the data transmission and subsequently conducted the performance measurements for each metric. It was employed a CBR source with messages generation rate equal to the lowest transmission rate among links of a route. Cross-layer interaction between the MAC and application layer obtains such rate information. We carried out thirty simulation rounds; the results average was calculated with 95% confidence interval.

Figures 9, 11, 13, 15 and 17 present the results of capacity for each assessed metric as function of the amount of demands/routes k accepted in the network. According to these figures, simulations were carried out with each metric choosing among channels of 5, 10 and 20 MHz width. In addition, we conducted simulations exclusively with 5 or 10 or 20MHz channel width. Figures 10, 12, 14, 16 and 18 present simulations with coexisting 5, 10 and 20 MHz channel widths. These figures show values of the percentage of established links in each channel width in function of the total amount of established links. Finally Figures 19 and 20 show a comparison of capacities obtained by the use of the metrics for selecting among the channels 5, 10 and 20MHz.

In Figure 9, we observe higher capacity values for WCETT metric obtained by selecting between 5, 10 or 20MHz channel widths. In this situation, according to Figure 10, the established links use 20 or 10 MHz channel widths. The use of WCETT metric determines the selection of links and routes with lower transmission time (see Equations 9 to 13 of section 4.1), as are the links that use channels of width 20 and 10MHz.

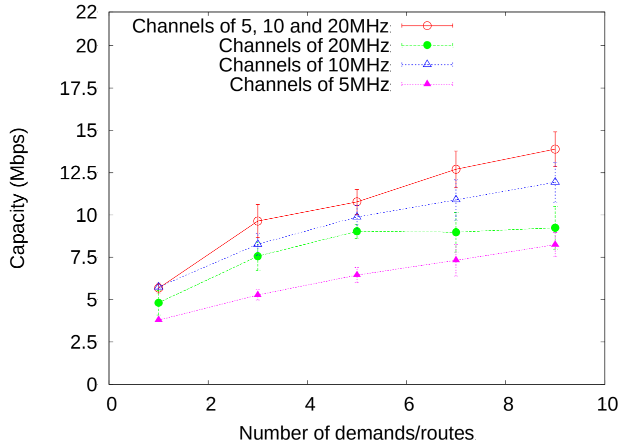

Figure 9. Capacity for WCETT metric

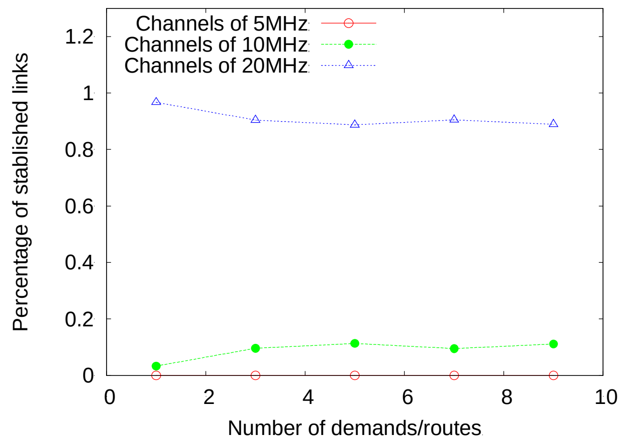

Figure 10. Percentage of established links in each channel width for WCETT metric

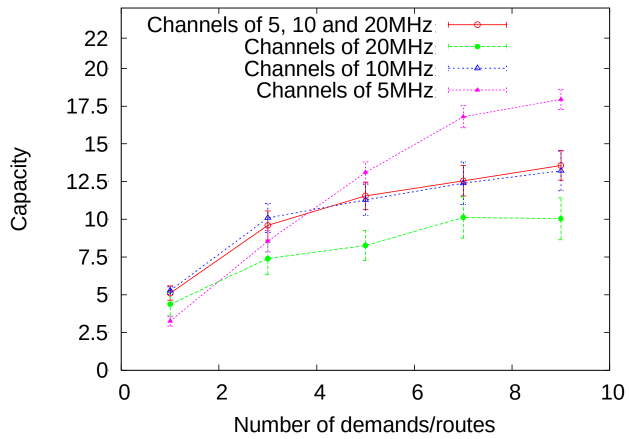

Figure 11. Capacity for EETT metric

In Figure 11, the use of EETT metric to select channel width determines the choice of links of 10 and 20 MHz channel width. This choice occurs since the metric values establish the selection of links in channels with lower transmission time, such as the case of links that use 10 and 20MHz channel widths, as can be seen in Figure 12. Considering this choice of channels, Figure 11 indicates that the capacity values, obtained by channel selection are close to the capacity by using exclusively 10MHz channel width. We can observe in the figure that when $k = 5$, initiates an increase of competing links for the channels; therefore, dividing the AS into a higher amount of 5MHz channels reduces contention for the channels and consequently offers higher capacity. EETT metric is not able to account for interference between channels with partially overlapped spectrum, thus, the metric values do not recommends the use of 5 MHz channel width in the situation of contention increasing.

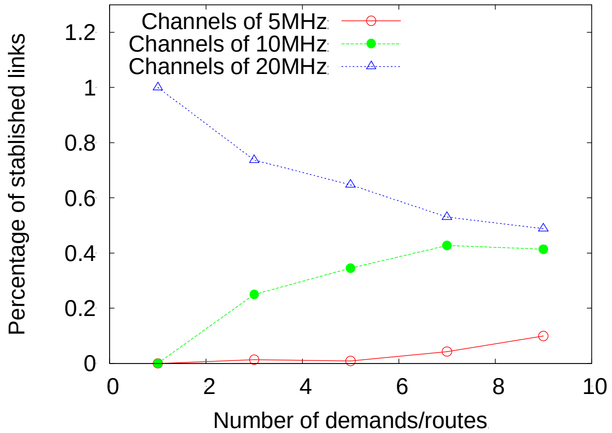

Figure 12. Percentage of established links while selecting channel width for EETT metric

Figure 13 illustrates that by using values of B-MTM metrics to select between 5, 10 and 20 MHz channel width, we obtain similar values of capacity to those of using only 10 MHz channel width. This occurs because the metric generates values that establish the choice of 10MHz channel width, since these channels offer higher theoretical capacity to a link that uses two radios, of the four existing, as output radios. Figure 14 shows the choice of 10 MHz channel width by the use of the metric, while selecting among existing channel widths; however, Figure 13 points that with the increase in the amount demands k, and consequently the increase in the contention for channels, 5MHz channel width offers the highest capacity when the metric is applied.

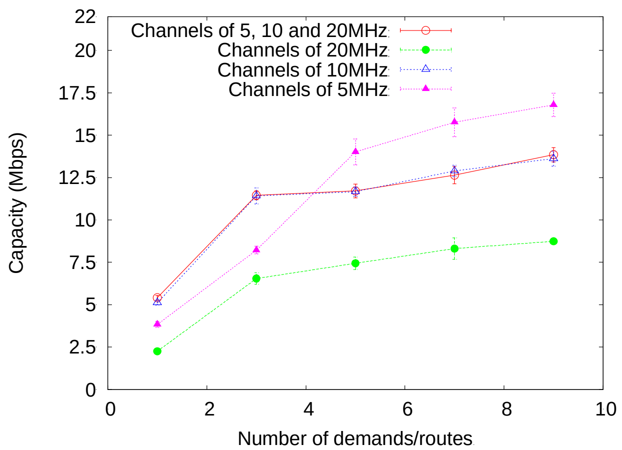

Figure 13. Capacity for B-MTM metric

Figure 15 shows the capacity results for MIC metric. The figure shows that MIC metric generates smaller capacity values with the use of 5MHz channel width. This occurs since for 5MHz channel width is greater the number of routers N_l of IRU_l term of MIC metric, which represents the number of interfered routers. Since it is the routing metric function to reduce the sum $\sum IRU_l$, when using $5MHz$ channel width, MIC favors to choose links with greater transmission range and that use modulations that transmit smaller number of bits per symbol. Among the individual employed channel widths, the $20MHz$ is the one that offers greater capacity values to MIC metric, until the number of demands is equal to five (05). After that, there is an increase in the contention for the medium and, the $10MHz$ channel width is the one that offers greater number of orthogonal channels in the available spectrum, thus offers greater capacity value to the network. Figure 16 shows that by selecting among all the available channel widths, the 10 and 20MHz values offer the greater capacity values to the network.

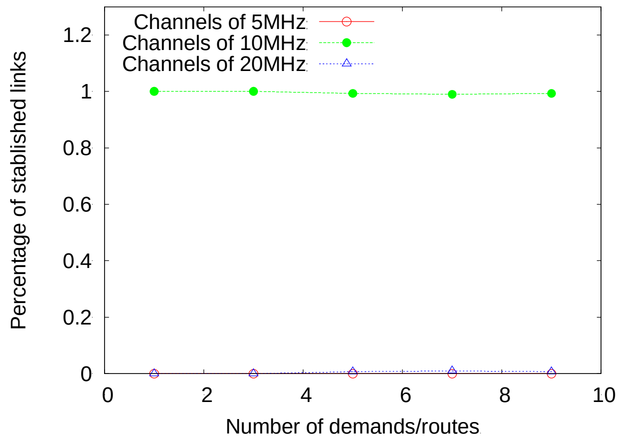

Figure 14. Percentage of established links while selecting channel width for B-MTM metric

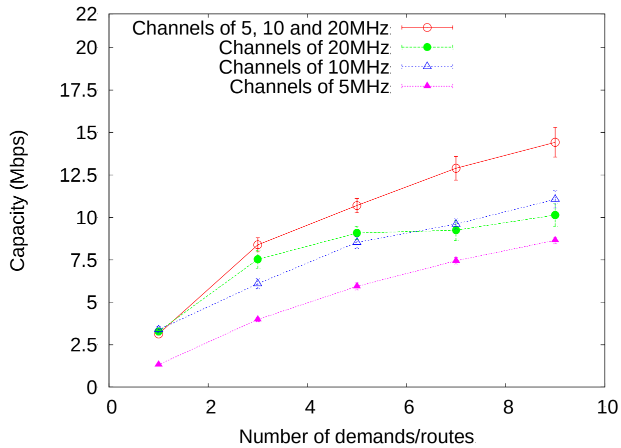

Figure 15. Capacity for MIC metric

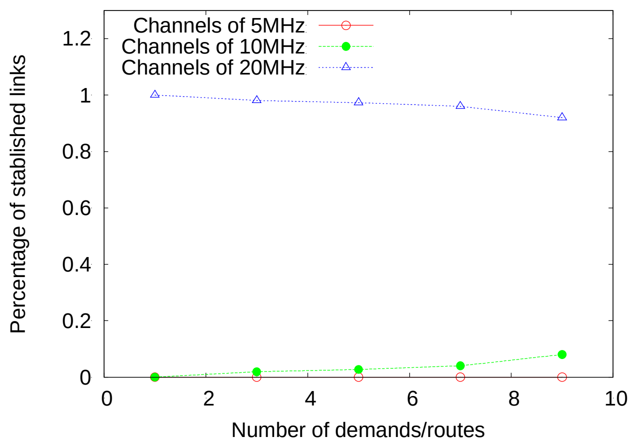

Figure 16. Percentage of established links while selecting channel width for MIC metric

Figure 17 shows the results for BEETT metric. This figure indicates that using exclusively 5MHz channel width generates higher values of capacity, when compared to the individual use of 10 and 20MHz channels widths. This is

because 5MHz channel width offers higher amount of orthogonal channels in which the use of the metric values tends to distribute the links equally in the channels. By using the metric values to select between 5, 10 and 20MHz channel widths, there is an increase in the network capacity. Figure 18 points that the metric applies 5 and 10 MHz channel width to provide higher values of capacity seen in Figure 17.
In Figure 19 we observe that MCWMR-BEETT metrics on being used for selecting between channel widths of 5, 10 and 20MHz offers higher capacity values when compared to the other metrics.

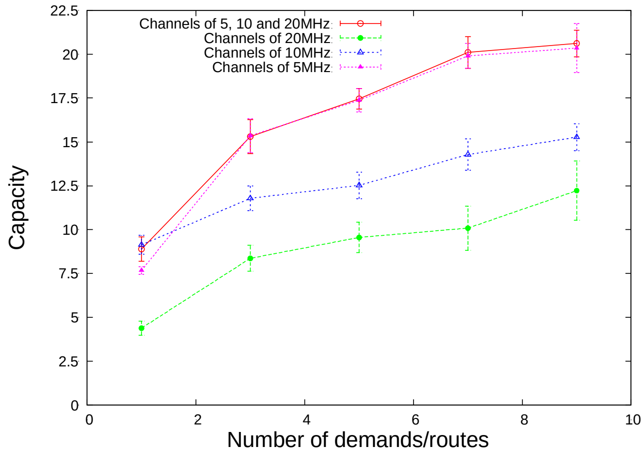

Figure 17. Capacity for BEETT metric

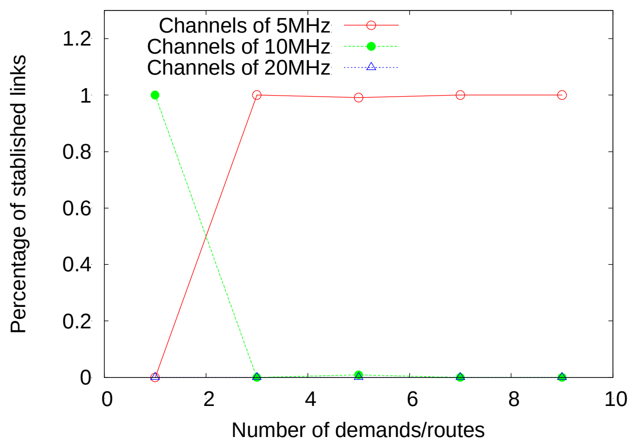

Figure 18. Percentage of established links while selecting channel width for BEETT metric

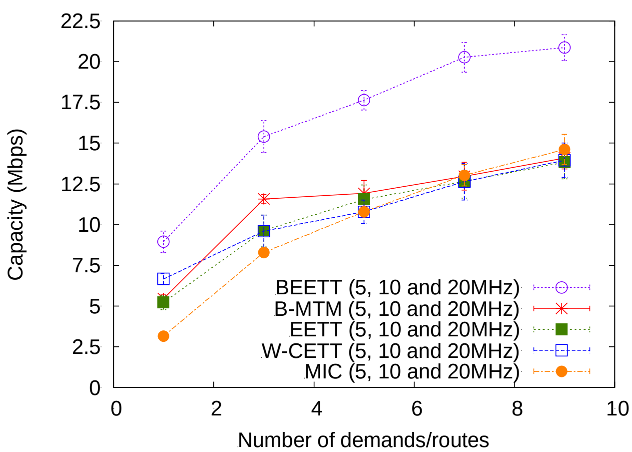

Figure 19. Obtained capacity when selecting among existing channel widths (5, 10 and 20MHz)

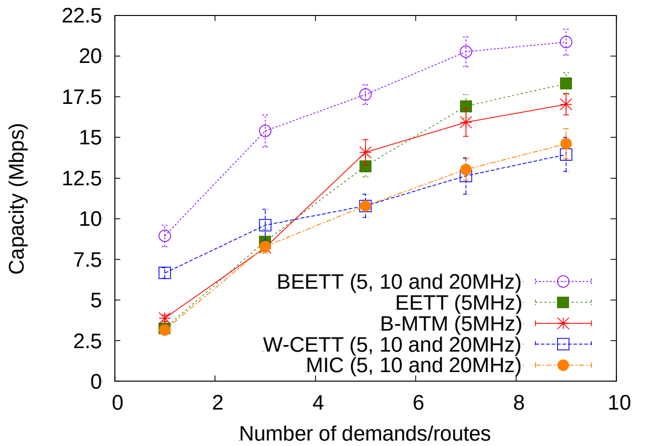

Figure 20. Greater obtained capacity values by selecting or using individual channel widths of 5, 10 and 20MHz)

Figure 20 shows an other example of the capacity gains obtained through MCWMR-BEETT metric when comparing its obtained capacity values when k = 9 with those of the remaining metrics. In this condition, higher capacity occurs when WCETT and MCWMR-BEETT metric select between 5, 10 and 20 MHz channel widths, and when EETT and B-MTM metrics use 5MHz channel width exclusively. In the abovementioned situation, the values of capacity obtained through WCETT, MIC, MCWMR-BEETT, EETT and B-MTM metrics are, respectively, 13.9, 14.6, 20.6, 17.9 and 16.7Mbits/s. In this case, MCWMR-BEETT metrics offers a gain above 15% compared with EETT, which offers the second highest value of capacity. There is a gain of 160% for the proposed metric when compared to EETT and MCWMR-BEETT with k = 1, in situation similar to the previous example, in which the former uses exclusively 5MHz channel width, and the second selects between all of the available channel widths.

6. Conclusions and future work

This paper proposed and assessed through simulations in NS-2, MCWMR-BEETT metric in scenarios with different channel widths. The assessments compared the results of MCWMR-BEETT proposal with different metrics for WMNs. According to the obtained results, we observe that the use of MCWMR-BEETT metrics enabled an increase in the capacity of MCMR-WMNs networks for the studied scenarios. Future work points to implement the proposed metric in real equipment and, in such scenario overcome problems related to synchronization and maintenance of links' and routes' communication when nodes move among channels of different widths.

7. Acknowledgement

This research was financed by FAPEAM (Foundation of research support of the state of Amazonas, Brazil)

References

[1] H. Zhai, Y. Fang, "Impact of routing metrics on path capacity in multirate and multihop wireless ad hoc networks," In Proceedings of the IEEE International Conference on Network Protocols, Washington, DC, USA, pp. 86–95, 2006.
[2] D. De Couto, D. Aguayo, J. Bicket, R. Morris, "A high-throughput path metric for multi-hop wireless routing," Wireless Networks, Vol. 11, No. 4, pp. 419-434, 2005.
[3] R. Chandra, R. Mahajan, T. Moscibroda, R. Raghavendra, P. Bahl," A case for adapting channel width in wireless

networks," Proceedings of the ACM SIGCOMM 2008 conference on Data communication, New York, NY, USA, pp. 135-146, 2008.
[4] C. B. Carvalho, J.F. De Rezende, "Routing in IEEE 802.11 wireless mesh networks with channel width adaptation," In Proceedings of Ad Hoc Networking Workshop (Med-Hoc-Net), Juan Les Pins, France, pp. 1-8, 2010.
[5] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. L. Ferrell, T. Moscibroda, S. Narlanka, Y. Wu, "Knows: Kognitiv networking over white spaces," In Proceedings of IEEE DySPAN, Dublin, Ireland, 2007.
[6] C.H.P. Augusto, C. B. Carvalho, M. W. R. da Silva, J. F. De Rezende, "The impact of joint routing and link scheduling on the performance of wireless mesh networks," In Proceedings of Local Computer Networks (LCN), Denver, CO, USA, pp. 80-81, 2010.
[7] M. Drini, T. Saadawi, "Link Lifetime Based Route Selection in Mobile Ad-Hoc Networks," International Journal of Communication Networks and Information Security (IJCNIS), Vol. 1, No. 3, pp. 31-39, 2009.
[8] V. Sarasvathi, N. Ch. S. N. Iyengar, S. Saha, "An Efficient Interference Aware Partially Overlapping Channel Assignment and Routing in Wireless Mesh Networks," International Journal of Communication Networks and Information Security (IJCNIS), Vol. 6, No. 1, pp. 52-61, 2014.
[9] C.H.P. Augusto, C. B. Carvalho, M. W. R. Da Silva, J. F. De Rezende, "REUSE: A combined routing and link scheduling mechanism for wireless mesh networks," Computer Communications, Vol. 34, No. 18, pp. 2207–2216, 2011.
[10] R. Draves, J. Padhye, B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks". In Proceedings of the 10th annual international conference on Mobile computing and networking, MobiCom, New York, NY, USA, pp. 114–128, 2004.
[11] Y. Yang, J. Wang, R. Kravets, "Interference-aware Load Balancing for Multihop Wireless Networks," Tech. Rep. UIUCDCS-R-2005-2526, Department of Computer Science, University of Illinois at Urbana-Champaign, pp. 1-16, 2005.
[12] W. Jiang, S. Liu, Y. Zhu, Z. Zhang, "Optimizing routing metrics for largescale multi-radio mesh networks," In International Conference on Wireless Communications, Networking and Mobile Computing - WiCom, Shanghai, China pp. 1550-1553, 2007.
[13] R.A. Calvo, J.P. Campo, "Adding multiple interface support in ns-2," Report, University of Cantabria, Spain. http://personales.unican.es/aguerocr/files/ucMultiIfacesSupport.pdf, 2007.
[14] Dei Gruppo Telecomunicazioni, "Dei80211mr library for the network simulator 2," http://telecom.dei.unipd.it/pages/read/58/, 2007.
[15] EPFL-IC, "No ad-hoc routing agent (noah)," http://icapeople.epfl.ch/widmer/uwb/ns-2/noah, 2011.
[16] T. Rappaport, "Wireless Communications: Principles and Practice," Prentice Hall PTR, Upper Saddle River, NJ, USA, 2001.
[17] L. Li, C. Zhang, "Optimal channel width adaptation, logical topology design, and routing in wireless mesh networks," EURASIP Journal on Wireless Communications and Networks, Vol. 2009, pp. 1-12, 2009.
[18] E. W. Dijkstra. "A note on two problems in connexion with graphs". Numerische Mathematik, Vol. 1, No. 1, pp. 269–271, December 1959.