Geographic Routing in IEEE 802.11 Wireless Networks with Channel Width Adaptation

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***Abstract*—In this paper, we propose two geographic routing metrics applied to wireless mesh networks that consider the use of channel width adaptation. The proposed metrics are evaluated through simulations jointly with a next hop channel width selection algorithm. The results show that the proposed metrics and algorithm generate greater throughput values when compared with existing geographic routing metrics.**

***Keywords*-Geographic Routing, Software Defined Radio, IEEE 802.11, Channel Width Adaptation, Routing Metric.**

I. Introduction

Selecting routes of higher throughput in wireless networks is a goal that has been treated in many works. Most of the previous work proposes topology-based routing algorithms and protocols [1]–[5]. In this sort of algorithm, each network node n maintains an information table with $n-1$ metric values, one for each other network node. The disadvantage of this approach is the large overhead of messages generated by the protocols in order to update the information of the network topology. As an alternative to topology-based routing, there is the geographic routing, where each node has positioning information about the destination node and also the location of their neighbors. Through this information, each node is able to determine the next communication hop, without the need of global knowledge of network topology.

Regarding the positioning information, the ever decreasing price of GPS technology [6] has motivated a greater use of algorithms that employ geographic routing. In addition to GPS, other promising technology, the Software Defined Radio (SDR), allows reconfiguring the channel width used by communication radios, and hence increase flow throughput in a wireless network. An example of SDR usage concerning the IEEE 802.11 OFDM physical layer [7] is the possibility of dynamically selecting among 5, 10 or 20MHz channels instead of being restricted to 20MHz channels only.

Based on [4] and [2], we apply the SDR and geographic routing technologies to propose the $G\text{-}BMTM$ (Geographic - Burst per MTM) and the G-B3ETT (Geographic - Burst per Estimated Exclusive Expected Transmission Time) metrics, which are evaluated through simulations jointly with a next hop channel width selection algorithm. Results show that the proposed metrics combined with the selection algorithm can provide greater throughput values when compared with the ADV and $NADV_{delay}$ metrics.

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To address these topics the paper is organized as follows. Section II reviews existing benchmark routing metrics. Section III explains the effects of channel width changing in the effective data rate and signal transmission range. Section IV presents the simulation model. Section V presents proposed routing metrics and channel width selection algorithm. Section VI describes performance evaluation. Section VII presents conclusions and future work.

II. Related Work

When using the ADV metric, according to [6], a source node S chooses a neighbor N as next hop to destination T as that with the greater advance to T. The ADV metric is calculated by $ADV(N) = D(S) - D(n)$, where $D(x)$ denotes the distance from the orthogonal projection of a generic node X on the line $\overline{ST}$. In Fig. 1, node S chooses node B as next hop since $ADV(B) > ADV(A)$.

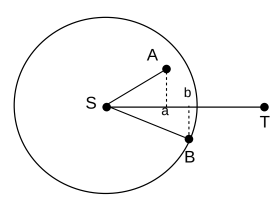


Fig. 1. *ADV routing metric*

As stated in [8], $NADV_{delay}$ metric normalizes the advance $ADV(N)$ by the transmission time C_{delay} of a link $\overline{SN}$ (See Equation (1)) with the aim of choosing links that have greater proximity to the destination and fewer transmission times.

$$NADV_{delay}(N) = ADV(N)/C_{delay} \tag{1}$$

The variable C_{delay} also includes the time spent with protocol overhead (e.g. control frames, back-off).

As proposed in [5], the Exclusive Expected Transmission Time (EETT) metric uses the concept of Interference Set (IS). The $IS(e_{i,j})$ is defined as the set of links that cannot simultaneously transmit with link $e_{i,j}$, including $e_{i,j}$ itself. The $EETT$ metric of link $e_{i,j}$ is defined in Equation (2) as the summation of Expected Transmission Times (ETTs) of links that are part of the $IS(e_{i,j}))$ set:

$$EETT_{i,j} = \sum_{e_{k,l} \in IS(e_{i,j})} ETT_{k,l} \quad (2)$$
$$ETT_{i,j} = ETX \cdot (S/B) \quad (3)$$
$$ETX_{i,j} = 1/(P_f \times P_r) \quad (4)$$

In reference to [2], the ETT metric is expressed in Equation (3), where S ($bits$) denotes the packet size and B ($bits/$s) is the raw data rate of the link. Also in Equation (3) and as in [3], the Expected Transmission Count metric (ETX) indicates the number of MAC layer transmissions necessary to successfully transmit a packet. ETX (Equation (4)) measures the link packet loss probability in both forward $(1/P_f)$ and reverse $(1/P_r)$ directions.

According to [4] and as presented in Equation (5), the B-MTM metric of a link $e_{i,j}$ considers the capacity in $bits/$s of nI radios that transmit in multiple channels of the same width w_{ϖ}. In (5), E_{DR} is the maximum effective data rate defined in Equation (6).

$$B\text{-}MTM^{nI}_{i,j,w_{\varpi}} = 1/E_{DR} \quad (5)$$

III. Impact of Channel Widths on the Effective Data Rate and Transmission Range

In Equation (6), the E_{DR} ($bits/$s) is the maximum effective data rate obtained in the MAC layer. The calculus considers the use of nI transmission interfaces that utilize channel width w_{ϖ} and transmission mode m_n. In the equation, L_{data} is the data packets length in bytes.

$$E^{w_{\varpi},m_n}_{DR} = (nI \cdot 8 \cdot L_{data})/T_T \quad (6)$$
$$T_T = CW + DIFS + T_{data} + SIFS + T_{ack} \quad (7)$$
$$T_{\alpha} = T_{pr} + T_{si} + T_{sym} \cdot ceil(\tfrac{L_{ser}+L_{tail}+8L_{\alpha}}{N_{DBPS}}) + T_{SE} \quad (8)$$

In Equation (7), $CW = [1, 31] * t_{slot}$ is the contention window[1]. The variables $t_{slot} = 20\mu s$, $DIFS = 50\mu s$ and $SIFS = 10\mu s$ assume well-know values [7]. The T_{DATA} and T_{ACK} variables represent the transmission times of data and ACK frames, respectively, both called T_{α} in Equation (8)[2].

In Equation (8) and Table I, T_{pr}, T_{si} and T_{sym} represent the transmission time of the synchronization preamble, the transmission time of the signal field, which indicates to the physical layer the transmission mode, and the time duration of an 802.11 OFDM symbol, respectively. The L_{SER} (16 $bits$) and L_{tail} (6 $bits$) variables represent the size of the service field, which is reserved for future applications, and the tail that marks the end of the OFDM frame, respectively. The variable L_{α} can assume the value L_{MAC} (34 $bytes$) plus L_{data} ($bytes$) corresponding to the MAC header plus data or the value L_{ACK} (14$bytes$) of the ACK frame.

[1]In the calculation, we use the average value, which is equal to $16 \times t_{slot}$

[2]Considered that ACK is transmitted with the same rate of the data frame

TABLE I
OFDM Physical layer times for 5, 10 and 20MHz channel widths [7].

Parameter	20MHz	10MHz	5MHz
T_{pr}	16μs	32μs	64μs
T_{si}	4μs	8μs	16μs
T_{sym}	4μs	8μs	16μs

At last, the N_{DBPS} variable (column 4 of Table II) represents the number of bits of information transmitted in one OFDM symbol and its values depend on a combination of modulation (column 2) and channel coding rate (column 3), which is called transmission mode or only mode (column 1), as stated in [7].

TABLE II
802.11 OFDM transmission modes

Mode	Modulation	Coding rate	N_{DBPS}
m_1	BPSK	1/2	24
m_2	BPSK	3/4	36
m_3	QPSK	1/2	48
m_4	QPSK	3/4	72
m_5	16-QAM	1/2	96
m_6	16-QAM	3/4	144
m_7	64-QAM	2/3	192
m_8	64-QAM	3/4	216

Using Equation (6), it is possible to assess the impact of using different channel widths on the maximum throughput of a source/destination pair. In the evaluation, we use L_{data} equal to 2000 $bytes$ and vary nI from 1 to 3 for 20MHz channel width and from 1 to 12 for 5MHz channel width.

In Fig. 2, the X-axis represents the OFDM transmission modes and the Y-axis shows the throughput in M$bits/$s. It is observed that with nI equal to 4 and 5MHz channels, i.e. a total of 20MHz occupied frequency bandwidth, a greater throughput than that achieved when using nI equal to 1 and 20MHz channel for all transmission modes is obtained. This gain in favor of channels of lower widths becomes more evident when comparing the throughput of 3 channels of 20MHz with the one of 12 channels of 5MHz, with both occupying a total of 60MHz.

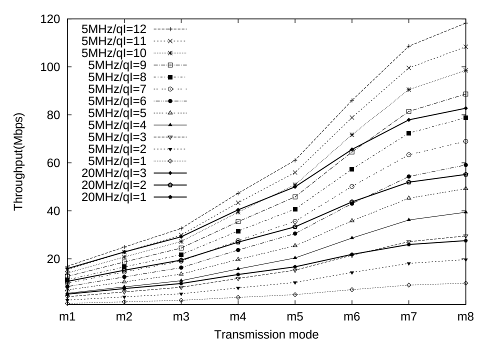


Fig. 2. Routes aggregated throughput (5 and 20MHz channel widths).

Altering channel width implies also in variations of the receiver sensitivity, and thus changes to the maximum distance the signal can spread being still intelligible by the receiver.

According to [9] and as in Equation (9), S_{min} is the minimum sensitivity (dBm), SNR_{min} is the minimum signal-to-noise ratio required for reception (mW), K is the Boltzmann constant, T_0 is the absolute temperature, B is the communication channel width (e.g. 5, 10 ou 20MHz) and N_f is the noise figure, which expresses the signal deterioration of receiver's internal circuit. Therefore, using Equation (10), we can estimate the receiver sensitivity gain, when reducing the communication channel width from value $B1$ to $B2$. If we do $B1 = 10\text{MHz}$ and $B2 = 20\text{MHz}$, for one same transmission mode (e.g m_1) and respective SNR_{min}, the relation assumes value $R \cong -3dB$. Thus, each time one divides channel width by two, one reduces 3 dB in minimum sensitivity to the same transmission mode.

$$S_{min} = SNR_{min} \cdot K \cdot T_0 \cdot B \cdot N_f \quad (9)$$

$$R = 10 \cdot \log_{10}(S_{min}^{B1} / S_{min}^{B2}) \quad (10)$$

The previous calculations explain the values of minimum sensitivity found in [7] and shown in Table III, which approximates the measurement results presented in [10].

TABLE III
MINIMUM SENSITIVITY VALUES FOR 5, 10 AND 20MHz CHANNEL WIDTHS

	Channel Widths		
Mode	20MHz	10MHz	5MHz
m_1	-82	-85	-88
m_2	-81	-84	-87
m_3	-79	-82	-85
m_4	-77	-80	-83
m_5	-74	-77	-80
m_6	-70	-73	-76
m_7	–66	-69	-72
m_8	–65	-68	-71

$$PL = P_T - P_R = 20log_{10}(\frac{4\pi f d0}{c}) + 10nlog_{10}(\frac{d}{d0}) \quad (11)$$

$$d = 10^{\frac{P_T - P_R - 20 \cdot log_{10}(4 \cdot \pi \cdot f \cdot d0/c)}{10 \cdot n}} \quad (12)$$

The values of Table III applied to log-distance path loss, can determine the maximum distance d between source and destination. According to Equation (11) in [11], we derive Equation (12), where $P_T = 17dBm$ is the transmission power and P_R is the reception power (applied minimum sensitivity values of Table III). The subtraction $P_T - P_R$ denotes the propagation path loss. The variable f is the signal frequency (2.4GHz is used), $d0$ is the reference distance (used 1m), c is the light speed in vacuum ($\simeq 3 \cdot 10^8\text{m/s}$), n is the propagation loss exponent (used 2.5). By applying Equation (12), we can estimate the proportional increase in transmission range when using channels of smaller widths. We call $d^{w_2,m_n}/d^{w_1,m_n}$ the ratio between the transmission ranges when using channel widths w_1 and w_2, both with the same modulation m_n. With this in mind and if we do $w_2 = 10\text{MHz}$, $w_1 = 20\text{MHz}$ and $m_n = 1$ (Table III), we verify a transmission range 1.32 times greater for 10MHz channels. The same previous calculation with $w_2 = 5\text{MHz}$ generates a transmission range 1.74 times greater for 5MHz channel width. This can reduce the number of hops of a end-to-end communication and increase transmission interference range.

IV. SIMULATION MODEL

As in [4], we modeled the wireless network using a graph $G(V, E)$ consisting of a set of vertexes $V = \{v_i\}_{1\times|V|}$ and a set of links (or edges) $E = \{e_{i,j,c}\}_{|V|\times|V|\times|C|}$. Edges can be established in a set of channels C. There is a set of flows $F = \{f_k\}_{1\times|F|}$ and each one is originated in a source node v_k and has as destination node v_l. Each flow f_k is associated with a route $Ro = \{ro_k\}_{1\times|Ro|}$, where $|Ro| = |F|$.

Concerning the communication channels, the IEEE 802.11 specification [7] allows the existence of 5, 10 and 20 MHz channel widths. Generalizing, we have assumed that the total frequency bandwidth (B_{TOT}) can be divided into a number of discrete orthogonal channels of width w_ϖ ($\varpi = 1, ..., |W|$, where W is the set of available channel widths). In this case, for each existing channel width w_ϖ, it is possible to divide the spectrum in B_{TOT}/w_ϖ non-overlapping channels of equal width, contained in a set $C^{w_\varpi} = \{c_d^{w_\varpi}\}_{1\times|C^{w_\varpi}|}$. Thus, the total number of channels in all available widths is given by $C = \bigcup_{\varpi=1}^{|W|} C^{w_\varpi}$. It can be noted that channels of different widths w_ϖ can overlap each other.

As in [12], we have used the designation *logical link* for each link $e_{i,j,c_d^{w_\varpi}}$ established between nodes v_i and v_j in channel $c_d^{w_\varpi}$. Also, we have called *physical link* e_{i,j,w_ϖ} the set of all logical links set up between nodes v_i and v_j using channels of the same width w_ϖ . In the rest of the paper, we use only link to designate a logical link.

In the following, we enumerate the other used notations:

- Logical Links Matrix: $E = \{e_{i,j,c_d^{w_\varpi}}\}_{|V|\times|V|\times|C|}$, $\forall\, e_{e,j,c_d^{w_\varpi}} \in \{0, 1\}$, represents the nodes that are within communication and carrier sense ranges (considered that RXThreshold is equal to CSThreshold). If $e_{i,j,c_d^{w_\varpi}} = 1$, node v_i can transmit to node v_j in channel $c_d^{w_\varpi}$. To determine the elements of this matrix, Equation (12) is used to calculate the maximum communication distance d. For that, the P_R variable is assigned to the minimum sensitivity value of m_1 transmission mode (mode with greater transmission range) of a certain channel width w_ϖ (e.g. in Table III the lowest minimum sensitivity value for 5 MHz is -88 dBm). P_T and n variables assume their associated values, e.g. 17 dBm and 2.5 respectively. If $d_{i,j} \leq d$, $e_{i,j,c_d^{w_\varpi}}$ assumes value 1.
- Transmission Times Matrix: $TX = \{tx_{i,j,c_d^{w_\varpi}}\}_{|V|\times|V|\times|C|}$, $\forall\, e_{i,j,c_d^{w_\varpi}} \in \mathbb{R}$, represents the transmission time of a L_{data} *bytes* data frame and corresponding ACK frame when using a channel $c_d^{w_\varpi}$. Values of this matrix are calculated for every pair of nodes that have $e_{i,j,c_d^{w_\varpi}}$ equal to 1. In this case, given the distance $d_{i,j}$, n and P_T, we calculate the received power $P_{R(i,j)}$ of a link by isolating P_R variable of Equation (11). After, we choose for each channel width w_ϖ, the transmission mode m_n that has minimum

sensitivity (Table III) immediately below the received power $P_{R(i,j)}$. The chosen transmission mode is the one which provides the lowest transmission time. After transmission mode selection, we use its N_{DBPS} value (Table II) to calculate the transmission time $tx_{i,j,c_d^{w_\varpi}}$ through Equation (7).

- Channel Occupancy Times Matrix: $TO = \{to_{i,j,c_d^{w_\varpi}}\}_{|V|\times|V|\times|C|} \ \forall \ e_{i,j,c_d^{w_\varpi}} \in \mathbb{R}$, represents airtime occupancy of channel $c_d^{w_\varpi}$. This matrix starts with all its values set to zero, representing that there are no transmissions in the network. When $to_{i,j,c_d^{w_\varpi}} = \beta$, this means that nodes v_i and v_j realize that channel $c_d^{w_\varpi}$ is used for a period of time equal to β. Each new occupied link $e_{k,l,c_e^{w_z}}$ (including $e_{i,j,c_d^{w_\varpi}}$ itself) that uses partially or totally the same frequency band of the channel $c_d^{w_\varpi}$ and is in the interference range of $e_{i,j,c_d^{w_\varpi}}$, makes $to_{i,j,c_d^{w_\varpi}}$ to be updated by $to_{i,j,c_d^{w_\varpi}} = to_{i,j,c_d^{w_\varpi}} + \sum tx_{k,l,c_e^{w_z}} \ \forall \ (e_{i,k,c_d^{w_\varpi}} = 1) \vee (e_{j,k,c_d^{w_\varpi}} = 1) \vee (e_{i,l,c_d^{w_\varpi}} = 1) \vee (e_{j,l,c_d^{w_\varpi}} = 1)$. The values of this matrix are used to calculate routes throughput and choose the channels with less airtime occupancy to be used by each new admitted network link.

It is considered that all nodes have information about the maximum frequency bandwidth that a physical link may occupy (B_{MAX}). For example, B_{MAX} equal to 20 MHz represents that a physical link e_{i,j,w_ϖ} can transmit using a maximum of $qI = B_{MAX}/w_\varpi$ transmission channels. Thus, if $B_{MAX} = 20$MHz and w_ϖ is equal to 5, 10 or 20 MHz, it can be used 4, 2 or 1 channels/interfaces in a physical link, respectively. We call $nI(i)$ the number of communication interfaces that a node i is equipped with.

To calculate the throughput obtained in different routes we use the model in [13], which we extended to scenarios with multiple transmission channels and multiple channel widths.

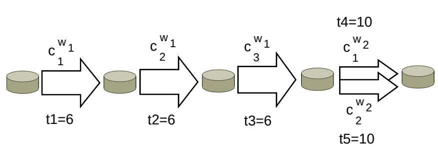


Fig. 3. Thoughput calculation model

In Fig. 3, all links are within interference range of each other. The route is composed of 4 links that occupy the channels c_1, c_2, c_3 of width w_1 and, c_1 and c_2 of width w_2. Links of width w_1 and w_2 have frame transmission times equal to 6 and 10s, respectively. The latter two links have higher airtime ($t4 = t5 = 10$s) since they are narrower. The route's throughput is equal to the lowest capacity of the links that compose it and is given by $min\{Ca_1, Ca_2, Ca_3, Ca_4\} = min\{\frac{1}{(t1+t4)}, \frac{1}{t2}, \frac{1}{t3}, \frac{2}{t1+t4}\} = \frac{1}{16}$, where Ca is the link capacity. Note that the throughput calculation of link 4 has a value 2 in the numerator, since two concurrent frames are transmitted using the 2 non-overlapping channels of this link.

In the Section VI, we perform calculations similar to the previous example to determine the throughput of the established routes. We have applied Equation (13) to determine the capacity of each used physical link. In the denominator of this equation, we use the values of the TO matrix to include the occupancy time perceived by the physical link e_{i,j,w_ϖ} [3].

$$Ca_{qI}^{w_\varpi} = \frac{min(qI, nI(i), nI(j)) \cdot L_{data} \cdot 8}{to_{i,j,c^{w_\varpi}}} \tag{13}$$

V. Proposed Metrics and Algorithm

G-B3ETT metric is based in EETT [5] and B-MTM [4] metrics. Similar to B-MTM, we also consider throughput capacity of the link in different channel widths w_ϖ. Likewise $EETT$ we also take into account the interference caused by other links, avoiding simultaneous transmissions. In Equation (14), $G\text{-}B3ETT_{i,j,w_\varpi}$ represents the metric value for physical link e_{i,j,w_ϖ}. The term min(qI,nI) determines the smaller value between transmission channels and available number of transmission interfaces. The variable L_{data} is the data packet length and $3ETT_{i,j,w_\varpi}$ is the Estimated $EETT$ value of the physical link. In Equation (15) the first term represents the estimated time that H hops $(h_1, ..., h_{\gamma=H})$ with transmission time $tx_{i,j,c_d^{w_\varpi}}$ in the same channel would occupy. In an example of H determination, we set $B_{TOT} = 60$MHz, $B_{MAX} = 20$MHz, channel width $w_\varpi = 20$MHz, $nI(i) = nI(j) = 2$. Applying Equation (17), we would have $K = 60\text{MHz}/min(2,2,1) \cdot 20\text{MHz} = 3$ physical links available for transmission. In this case, (see Fig. 4) we would have an estimation of $H = 2$ hops in the same physical link in the route (intra-flow interference). The term $min(to_{i,j,w_\varpi})$ (Equation (15)) counts for the physical link with the minimum airtime occupancy and aims to estimate links' inter-flow interference.

$$G\text{-}B3ETT_{i,j,w_\varpi} = \frac{min(qI,nI) \cdot L_{data} \cdot 8}{3ETT_{i,j,w_\varpi}} \tag{14}$$

$$3ETT_{i,j,w_\varpi} = H \cdot tx_{i,j,c_d^{w_\varpi}} + min(to_{i,j,w_\varpi}) \tag{15}$$

$$H = ceil(\frac{\overline{ST}}{ADV(N)} \cdot \frac{1}{K}), \ S = i, N = j \tag{16}$$

$$K = \frac{B_{TOT}}{min(nI(i), nI(j), qI) \cdot w_\varpi} \tag{17}$$

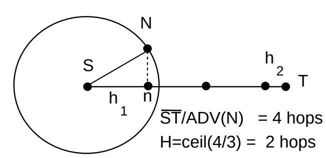


Fig. 4. *G-B3ETT: Calculation of H parameter*

Our second proposal called $G\text{-}BMTM$, is given by Equation (18). ADV is the advance between nodes v_i and v_j and $B\text{-}MTM_{i,j,w_\varpi}^{min(qI,nI)}$ is the metric given in Equation (5).

$$G\text{-}BMTM_{i,j,w_\varpi}^{min(qI,nI)} = ADV \cdot B\text{-}MTM_{i,j,w_\varpi}^{min(qI,nI)} \tag{18}$$

[3] to_{i,j,w_ϖ} accounts for the physical linke_{i,j,w_ϖ} occupancy time that is determined by the maximum value of occupancy time of the logical links that compose it.

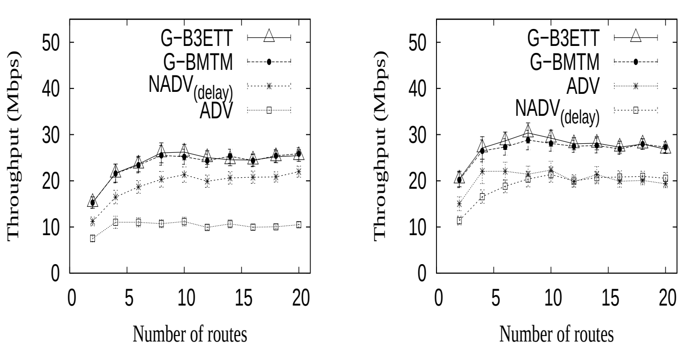
We use algorithm1 to select the channel width for each hop of a flow f_k (line 1). For each next hop to the destination (line 4), the algorithm stores in the matrix $metricMatrix$ (line 10) the values of metrics for each channel width w_ϖ (line 5) and each neighbor j (line 6). The function max returns the next hop and its corresponding channel width with the greater metric value (line 11). The functions on lines 12 and 13 append to its first argument the chosen next hop node ID and channel width of each hop for a route r_k. After the execution of this algorithm the throughput calculations of Section IV are done.

Algorithm 1: Selects links' channel width

1 **foreach** *flow* f_k **do**
2   $source = v_k$;
3   $destination = v_l$;
4   **while** $nextHop \neq destination$ **do**
5   **foreach** *channel width* w_ϖ **do**
6   **foreach** *neighbor node* j **do**
7   //For other metrics applied their values
8   //ADV_{i,j,w_ϖ} or $NADV_{delay}(N)_{i,j,w_\varpi}$
9   //or $G\text{-}BMTM_{i,j,w_\varpi}$
10   metricMatrix($source, j, w_\varpi$)=$G\text{-}B3ETT^{qI}_{source,j,w_\varpi}$;
11   (betterChanWidth,nextHop) = max(metricMatrix($source, j, w_\varpi$));
12   append(hopsOfRoute(k),nextHop);
13   append(chanWidthOfRoute(k),betterChanWidth);
14   source=nextHop;

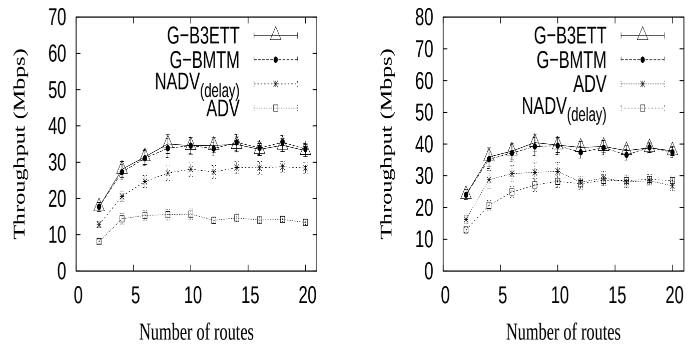
VI. Performance Evaluation

We simulated a scenario of $1000\text{m} \times 1000\text{m}$ with 100 nodes randomly spread. The number of flows f_k is varied from 2 to 20, and each flow has source and destination nodes randomly selected. The frame size is 2000 bytes and $n = 2.5$ (path loss exponent). B_{MAX} variable is assigned to 20MHz. Variables B_{TOT} and nI (number of transmission interfaces/node) assume values shown in Fig. 5 and 6. For each configuration, we made 100 simulations with a confidence interval of 95%. Results show that in all simulated scenarios the proposed metrics obtain greater throughput when compared to the benchmark metrics. Although $G\text{-}B3ETT$ metric gives results slightly higher than $G\text{-}BMTM$ metric, the first metric has more complex determination.



(a) 4 interfaces per node. (b) 8 interfaces per node.

Fig. 5. Routes aggregated throughput.($B_{TOT} = 60\text{MHz}$)



(a) 4 interfaces per node. (b) 8 interfaces per node.

Fig. 6. Routes aggregated throughput.($B_{TOT} = 80\text{MHz}$)

VII. Conclusion

In this paper, we proposed $B\text{-}MTM$ and $G\text{-}B3ETT$ geographic routing metrics for wireless mesh networks that are able to use different channel widths. Also, a channel width selection algorithm that works jointly with the proposed routing metrics is proposed. Our proposal was compared through simulations with existing ADV and $NADV_{delay}$ routing metrics. The obtained results show that the proposal obtains better throughput performance. Future work points to the implementation of the proposed metrics through a protocol in Network Simulator (NS-2) and comparison to other geographic and/or topology-based routing protocols.

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