

Performance Analysis of Broadcasting in Small-Scale Multi-Radio Multi-Channel Wireless Mesh Networks

Avid Avokh^{*}, Ghasem Mirjalily^{**}

^{*} *Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Isfahan, Iran.*

^{**} *Faculty of Electrical and Computer Engineering, Computer and Communication Networks Research Group, Yazd University, Yazd, Iran.*

aavokh@stu.yazduni.ac.ir , mirjalily@yazduni.ac.ir

Abstract— Multi Radio Multi Channel Wireless Mesh Networks (MRMC-WMNs) are undergoing rapid progress and inspiring numerous deployments. These networks require carefully assignment of resources and load balancing to provide the quality guarantees to traffic flows. Load balancing avoids the creation of bottlenecks and increases the network efficiency. Certainly, we need a benchmark to compare the performance of different load balancing mechanisms. In this paper, we consider the scenario of bandwidth-guaranteed broadcast sessions, where each session has a specific bandwidth requirement. The aim of this research is to analyze the performance of broadcasting in small-scale MRMC-WMNs. By considering Wireless Broadcast Advantage (WBA), we formulate channel and node constraints and propose “*Traffic Engineering Efficiency*” to evaluate the load balancing ability of algorithms. Deriving analytical relationships between throughput, number of transmissions, node and channel utilization is other contribution of this paper. In order to confirm the accuracy of derived analysis, we present some simulations on typical networks.

Keywords- Broadcasting; Load balancing; MRMC-WMN; Number of Transmissions; Throughput; Utilization; WBA.

I. INTRODUCTION

In the recent years, public deployment of wireless networks has quickly increased, because their significant advantages over wired networks. In this regard, Wireless Mesh Networks (WMNs) as next generation wireless broadband networks are being increasingly deployed to provide and extend access to the Internet. WMNs are typically a new class of multi-hop wireless networks with self-organization and self-configuration capabilities [1]. They provide improved reliability as well as larger coverage and reduce equipment cost. A typical WMN consists of three types of nodes: gateway, mesh router, and mesh client [1,2]. Gateways enable the integration of WMNs with different technologies, such as IEEE802.11 (WLAN), IEEE802.16 (WiMAX) and wired networks. Mesh routers have minimal mobility and function as both a relay node and an Access Point (AP). As a relay node, mesh routers form a mesh backbone among themselves and forward packets in a multi-hop fashion from the source node to the destination node, and as an access point, they forward packets from or toward the associated mobile clients.

Efficient utilization of resources is one of the most challenging issues in WMNs. These networks suffer from the degradation of capacity due to interference problem. An effective approach to relieve this problem is using the technology of Multi-Channel Multi-Radio (MCMR) [2-8]. In

this way, every mesh router is equipped with multiple Network Interface Cards (NICs) tuned to orthogonal channels. Ability to utilize multiple channels substantially leads to efficient spectrum utilization and increases the capacity of network. The nodes can transmit packets simultaneously on distinct channels without causing collisions and interference. However, since the number of available channels is limited, some links interfere with each other and cannot be active at the same time. So, a proper channel assignment and routing strategy can significantly alleviate the capacity problem and increase the bandwidth available to the network [2].

Broadcast Routing is an important network service which reduces traffic by simultaneously delivering a single stream of packets to all network nodes in an efficient manner. It provides underlying support for multimedia applications such as IP-TV, video conference, video and audio on-demand service, distant education, and online games. A fundamental difference between broadcast routing in wireless and wired networks is the broadcast nature of the wireless channels, results in a well-known property named Wireless Broadcast Advantage (WBA) [5-7]. Based on this property, all neighbors can receive the same copy of data with the source node only transmitting once. In this regard, an objective is that each broadcast flow uses the minimally feasible network resources. This maximizes the total amount of broadcast sessions that the network may simultaneously transport.

Actually, there are two major constraints in wireless mesh networks: channel capacity constraint and node capacity constraint. Because of the shared nature of wireless medium, the transmission from a node will be affected by other co-channel transmissions within the interference range of that node. On the other hand, in many practical situations, channels may have enough capacity but nodes, due to insufficient capacity may be congested [5]. These constraints may seriously limit the network performance.

In order to evaluate the performance of the networks, there are several criteria which usually affect on each other. So, it is not possible to draw a certain boundary between them. Certainly, having a prior knowledge about the bounds of criteria and also relationship between them provide more options for the system administrator to control the features of the network. The main research objective of this paper is to analyze the broadcasting performance of the small-scaled MRMC-WMNs. We focus on the scenario of bandwidth-guaranteed broadcast sessions, where each call has a specific bandwidth requirement. In this regard, by considering WBA

and interference constraints, we derive analytical relationships between throughput, node utilization, number of transmissions and channel utilization. We also introduce the “*Traffic Engineering Efficiency*” to evaluate the quality of solutions obtained by any approximation algorithm. As the best of our knowledge, this paper is the first one which studies the performance of broadcasting in small-scale MRMC-WMNs.

The rest of this paper is organized as follows: Section II reviews the previous related works. Section III introduces the details of network model and problem assumptions that will be used in this paper. In Section IV, we first introduce the used variables and then we formulate the problem. In section V, we drive the performance analysis of broadcasting in small-scale MRMC-WMNs. The evaluation of proposed analysis is presented in Section VI and finally, some concluding remarks are provided in Section VII.

II. RELATED WORK

In recent years, MRMC-WMNs have been studied extensively for unicast communications. Some previous works endeavored to heuristically improve the systems’ performance, while others focused on the optimization algorithms for satisfying the clients’ traffic demands. In this regard, several unicast routing metrics (such as ETX, ETT, WCETT, WCCETT, MIC, iAWARE, etc [1, 3]) have been proposed to improve the routing performance as well as the network capability to satisfy the requirements of certain applications.

Although, in the context of unicast communications, the channel assignment / routing problem has been extensively studied, little work has been done on the broadcast and multicast traffics. In recent years, some authors address this issue in WMNs [4-9]. Roy et al. [9] studied the link-quality multicast routing metrics in single-radio single-channel WMNs. They pointed out the difference between unicast and multicast routing, and proposed five improved multicast metric. In [4], authors focus to investigate multicast routing metrics in MRMC-WMNs. They propose two load-aware metrics named FLMM and FLMM^R. Although both metrics count channel diversity, interference and wireless broadcast advantage, the later further considers the unreliability of MAC multicast.

In [5], authors consider the problem of constructing bandwidth-guaranteed multicast and broadcast tree in MRMC-WMNs. They focus on the scenario of dynamic call arrival and try to maximize the call acceptance rate of the network. The idea of this paper is that if the carried load on both the most-heavily loaded channel and the most-heavily loaded node is minimized, the traffic load in the network will be balanced. In this way, the authors first present an ILP formulation to construct bandwidth-guaranteed tree. Then, they introduce efficient heuristic greedy expansion and LC-SPF for broadcast and multicast tree Construction, respectively.

In [6,7], the objective is to find Minimum Cost Multicast Tree (MCMT) in MRMC-WMNs. In [6], authors propose a multicast routing named Multi Channel Minimum Number of Transmissions (MCMNT) that takes into account WBA and channel diversity to minimize the amount of network bandwidth consumed by the routing tree. Liu and Liao [7] prove that the MCMT problem in MRMC-WMNs is NP-hard. They define the cost of a multicast tree as the number of transmissions and formulated the MCMT problem by an ILP

model. They also propose a heuristic polynomial-time near-optimal algorithm called Wireless Closest Terminal Branching (WCTB). In the context of multi-rate MRMC-WMNs, Qadir and et al. address the issue of minimizing the broadcast delay in a distributed fashion [8]. They first propose a framework that by exploiting the rate and channel diversity calculates a set of forwarding nodes and their transmission rates irrespective of the broadcast source. Thereafter, a forwarding tree is constructed taking into consideration the source of broadcast.

After growing interest to fundamentally understand the capacity limitations of regular wireless networks [10,11], recently, the study of capacity in MRMC-WMNs has also attracted attention of some research groups. For example, the research work presented in [12] focuses on how to determine an upper bound on the maximum throughput from mesh clients to the Internet (or vice versa) for multi-radio wireless mesh networks in the case of the number of channels for assignment being high enough to meet the interference-free assumption.

III. NETWORK MODEL AND ASSUMPTIONS

In this section, we present the network model and assumptions that will be used in this paper. First consider a typical MRMC-WMN consists of n stationary mesh routers which each one (e.g., router x) is equipped with $|NIC|_x$ half-duplex radios. There are K orthogonal channels in the network. Each radio is tuned to a specific channel. As a result, the number of distinct channels that can be assigned to a node is bounded by the number of NICs it has. Practically, due to intra-node interference, it is not useful to have two radios tuned to the same channel at a given node. So, in order to efficiently utilize the network resources, we assume that for any node, the radios tuned to the different channels. It is also assumed a single transmission rate for all link-layer data multicasts. The radios are characterized by the identical transmission range and by the same interference range (d_{intf}).

We model the network by a directed graph $G = (V, E)$, where $V = \{v_1, v_2, \dots, v_n\}$ is the set of vertices represents n mesh routers and E denotes the set of communication links between nodes. Clearly, two nodes (e.g., x and y) are directly connected and form a communication link if and only if they are within the transmission range of each other and share a common channel. If x and y are directly connected, corresponding edge in the graph is denoted by (x,y) and presenting a link that is incident from node x to node y . Although we model the network as a directed graph, the connectivity and the channel assignment between any two adjacent nodes are assumed symmetric. That is, if node x is within the transmission range of node y , then y is also within the transmission range of x . Furthermore, if link (x,y) is bounded to channel k , then link (y,x) also uses channel k .

In this paper, we suppose a conflict-free reservation-based MAC protocol. Certainly, we will analyze the scheduling possibility of each broadcast flow under interference constraint and network capacity. In this regard, we use the protocol interference model well known as receiver conflict avoidance interference model [5,10]. According to this model, data transmission on link (x,y) is interfered by the data transmission on link (v,w) if and only if both of them use the same channel and node v be placed in interference range of node y . So, Conflict-free transmission is ensured by assigning nodes within each other’s interference range to either send on

different non-overlapped channels, or send on the same channel but at different times.

We consider the scenario of bandwidth-guaranteed broadcast call arrivals. On-demand sessions arrive dynamically without any prior knowledge of future arrivals. The traffic model of each session is assumed Constant Bit Rate (CBR) so that each session (e.g., session j) requires broadcasting a traffic load denoted by tr_s^j . Practically, the channel assignment strategy will likely be dictated by various factors, including the presence of unicast traffic on the network. So, it is assumed the channel assignment is done independently from broadcasting framework and no channel switching is allowed.

IV. PROBLEM FORMULATION

In MRMC-WMNs, due to the limited number of radios and the shared nature of wireless medium, there are two major constraints: channel constraints and node constraints. In this section, we define some essential variables and metrics that will be used in our analytic model. Besides, we formulate above constraints for the described network model. The capacity of i^{th} mesh router ($C(i)$) can be defined as:

$$C(i) = |NIC|_i c_0, \quad (1)$$

where c_0 is the raw capacity of channels. Also, we can define the sent traffic load ($l_s(i)$) and received traffic load ($l_r(i)$) of i^{th} mesh router as:

$$l_s(i) = \sum_{b=1}^{|NIC|_i} l_{s_b}(i), \quad l_r(i) = \sum_{b=1}^{|NIC|_i} l_{r_b}(i) \quad i=1,2, \dots, n. \quad (2, 3)$$

Where $l_{s_b}(i)$ and $l_{r_b}(i)$ are sent and received traffic load of b^{th} radio on i^{th} mesh router, respectively. Accordingly, for the total traffic load of a node (e.g. node i) we have:

$$l(i) = l_s(i) + l_r(i). \quad (4)$$

According to node capacity constraint, to avoid node overload, it is required that:

$$l_{s_b}(i) + l_{r_b}(i) \leq c_0, \\ l(i) \leq C(i), \quad \forall i=1,2, \dots, n. \quad (5)$$

Let l_i^j denotes the created load by j^{th} session on i^{th} node. So, the total load of i^{th} node ($l(i)$) can be expressed as follows:

$$l(i) = \sum_{j=1}^{n_s} l_i^j \quad i=1,2, \dots, n, \quad (6)$$

where n_s is the number of feasible sessions. Clearly, l_i^j depends on the role of node i at the j^{th} broadcast tree (T^j) which can be one of the three kinds of nodes, including source node, relay nodes and leaf nodes. A relay node has to transmit the packets from its parent to its children. A leaf node does not need to relay data and play only the role of destination.

Actually, each broadcast session (T^j) is comprised of a group of MAC Multicast Transmissions ($MMT(i, T^j, k)$), which correspond to transmission of node i on channel k . By

definition [7], the Number of Transmissions for node i at the j^{th} broadcast tree (NT_i^j) is:

$$NT_i^j = \sum_{k \in K} q_{i,k}^j, \quad (7)$$

where K denotes the set of K available orthogonal channels and $q_{i,k}^j$ is a binary variable which $q_{i,k}^j = 1$ if node i is a forwarding node on k^{th} channel at the j^{th} broadcast tree, otherwise, $q_{i,k}^j = 0$. In each broadcast session (T^j), all nodes (except source node) have only one parent. Unlike leaf nodes which only play the role of the child, forwarding nodes act as both parent and child; in the role of a child node, they receive data from corresponding parent and in the role of parent node, they send traffic to their children. So, the created load by j^{th} session on i^{th} node can be formalized as follows:

$$l_i^j = \begin{cases} tr_s^j (1 + NT_i^j) & \text{if } i \in FWD^j \\ tr_s^j \times NT_i^j & \text{if } i = s^j \\ tr_s^j & \text{if } i \in leaf^j \end{cases}, \quad (8)$$

where s^j , FWD^j and $leaf^j$ are the source, the set of forwarding nodes and the set of leaf nodes at j^{th} tree, respectively. By defining the utilization of i^{th} mesh router ($U(i)$):

$$U(i) = \frac{1}{C(i)} \sum_{j=1}^{n_s} l_i^j, \quad (9)$$

we can compute the average utilization of nodes as follows:

$$\bar{U} = \frac{1}{n} \sum_{i=1}^n U(i). \quad (10)$$

Also, by defining the total number of transmissions for j^{th} broadcast tree ($NT(T^j)$):

$$NT(T^j) = \sum_{i \in \{s^j, FWD^j\}} \sum_{k \in K} q_{i,k}^j, \quad (11)$$

the average number of transmissions ($\overline{NT}$) can be expressed as follows:

$$\overline{NT} = \frac{1}{n_s} \sum_{j=1}^{n_s} \sum_{i \in \{s^j, FWD^j\}} \sum_{k \in K} q_{i,k}^j. \quad (12)$$

On the other hand, because of the shared nature of wireless medium, the channel will be affected by other MAC multicast transmissions within the interference range of the concerned node. So, channel utilization differs depending on the "observing" node's location. By definition, the utilization of channel k as observed by a node (e.g. node y) is the total sent traffic of all nodes within node y 's interference range " $intf(y)$ " (including node y) on channel k [5]. The channel constraint for feasibility of n_s session's flows is:

$$(X_y^k = \sum_{j=1}^{n_s} \sum_{i \in intf(y)} \frac{tr_s^j}{c_0} q_{i,k}^j) \leq 1, \quad \forall k \in K, \forall y \in V, \quad (13)$$

where X_y^k is the utilization of channel k as observed by node y .

Theorem1: In described model, n_s bandwidth-guaranteed broadcast sessions are feasible and schedulable if constraint (5) and (13) are satisfied.

Proof: the proof can be found in [5]. ■

Obviously, in this paper, due to the described network model and problem assumptions, it is clear that condition (13) satisfies condition (5). Therefore, the broadcast sessions are feasible only if the constraint (13) is satisfied. Actually, a call admission control must reject sessions which have no feasibility. It is desired to maximize the amount of admitted broadcast load. Here, as described in [13], we define the “goodness” of network by the First Rejected Session (FRS). Also, we define the network throughput (τ) as the sum of traffic load of all admitted feasible broadcast sessions:

$$\tau = \sum_{j=1}^{n_s} tr_s^j. \quad (14)$$

In the rest, we consider small-scaled MRMC-WMNs. Actually these networks can provide broadband wireless services for various applications in rural, and campus scales. Here, a small-scaled MRMC-WMN is defined as a network with n mesh routers arbitrarily distributed over a $L \times L$ area such that $L \leq d_{inf} / \sqrt{2}$. It is worth to note that this condition is considered for the worst case. In practice, this issue has more degrees of freedom.

V. PERFORMANCE ANALYSIS OF SMALL-SCALE MRMC-WMNS

In this section, we analytically study the performance of QoS broadcasting in MRMC-WMNs.

Theorem 2: Assume all sessions broadcast the same traffic load (i.e., $tr_s^j = T_0$), and the capacities of all nodes in the network are also identical (i.e., $|NIC|_i = |NIC|$ and consequently $C(i) = C$); The average number of transmissions ($\overline{NT}$) is equal to:

$$\overline{NT} = \frac{nC}{n_s T_0} \overline{U} - n + 1, \quad (15)$$

where n is the number of mesh routers, n_s denotes the number of feasible sessions and $\overline{U}$ is the average utilization of nodes.

Proof: By using Eq. 9 and Eq.10, and by considering $C(i)=C$, we can write:

$$\overline{U} = \frac{1}{nC} \sum_{j=1}^{n_s} \sum_{i=1}^n l_i^j. \quad (16)$$

Now, using Eq. 8 and extending the above equation in term of l_i^j for three kinds of nodes (i.e., source node, forwarding nodes and leaf nodes), we have:

$$\overline{U} = \frac{1}{nC} \sum_{j=1}^{n_s} \left(\sum_{i \in FWD^j} tr_s^j (1 + NT_i^j) + tr_s^j NT_s^j + \sum_{i \in leaf^j} tr_s^j \right), \quad (17)$$

where NT_s^j is the number of transmissions for source node at the j^{th} tree. Now, by considering $tr_s^j = T_0$, we can write:

$$\overline{U} = \frac{T_0}{nC} \sum_{j=1}^{n_s} \left(\sum_{i \in \{s^j, FWD^j\}} NT_i^j + |FWD^j| + |leaf^j| \right), \quad (18)$$

where $|FWD^j|$ and $|leaf^j|$ are the number of forwarding nodes and leaf nodes at j^{th} broadcast tree, respectively. Since a broadcast session spans all n mesh routers, it is clear that:

$$|FWD^j| + |leaf^j| + 1 = n. \quad (19)$$

So, we can rewrite average utilization of nodes as follows:

$$\overline{U} = \frac{T_0}{nC} \sum_{j=1}^{n_s} \left(\sum_{i \in \{s^j, FWD^j\}} NT_i^j + n - 1 \right). \quad (20)$$

Therefore:

$$\overline{U} = \frac{T_0}{nC} \left[\sum_{j=1}^{n_s} \sum_{i \in \{s^j, FWD^j\}} NT_i^j + \sum_{j=1}^{n_s} (n - 1) \right]. \quad (21)$$

On the other hand, according to Eq.7 and Eq.12, we know that:

$$\overline{NT} = \frac{1}{n_s} \sum_{j=1}^{n_s} \sum_{i \in \{s^j, FWD^j\}} NT_i^j. \quad (22)$$

So, we have:

$$\overline{U} = \frac{n_s T_0}{nC} [\overline{NT} + n - 1] \Rightarrow \overline{NT} = \frac{nC}{n_s T_0} \overline{U} - n + 1. \quad (23)$$

■

Recall the definition of small-scale MRMC-WMNs. It is clear that in such networks, all of the mesh routers are located in interference range of each other; so, the utilization of channel k as observed by any node is identical. Therefore, we can define the utilization of k^{th} channel (X^k) and the average utilization of channels ($\overline{X}$) as follows, respectively:

$$X^k = \sum_{j=1}^{n_s} \sum_{i \in \{s^j, FWD^j\}} \frac{tr_s^j}{c_0} q_{i,k}^j, \quad \forall k \in \mathbf{K}, \quad (24)$$

$$\overline{X} = \frac{1}{K} \sum_{k=1}^K X^k. \quad (25)$$

Theorem3: Consider the conditions of theorem 2. The throughput (τ) can be expressed as a function of the average node utilization ($\overline{U}$) and the average channel utilization ($\overline{X}$):

$$\tau = \frac{c_0}{n-1} \left(n |NIC| \overline{U} - K \overline{X} \right). \quad (26)$$

Proof: By writing Eq. 24 for all K available orthogonal (non-overlapping) channels and summing them together, we can rewrite the average utilization of channels as follows:

$$\sum_{k=1}^K X^k = \sum_{j=1}^{n_s} \sum_{i \in \{s^j, FWD^j\}} \frac{tr_s^j}{c_0} (q_{i,1}^j + q_{i,2}^j + \dots + q_{i,K}^j), \quad (27)$$

$$\bar{X} = \frac{1}{K} \sum_{j=1}^{n_s} \sum_{k=1}^K \sum_{i \in \{s^j, FWD^j\}} \frac{tr_s^j}{c_0} q_{i,k}^j. \quad (28)$$

Assuming $tr_s^j = T_0$ and using Eq. 12, we have:

$$\bar{X} = \overline{NT} \frac{n_s T_0}{K c_0}. \quad (29)$$

Now, by considering $\tau = n_s T_0$, $C = |NIC| c_0$ and replacing $\overline{NT}$ with its obtained value in Eq.15, the throughput express as follows:

$$\tau = \frac{c_0}{n-1} \left(n |NIC| \bar{U} - K \bar{X} \right), \quad \blacksquare$$

In general, Eq.13 is a sufficient condition for scheduling feasibility. But it is too conservative and considers the worst case. To see this, suppose two transmissions which interfere with reception of a typical receiver but do not interfere with each other. Although they can happen concurrently, Eq.13 considers two different time slot for them. In the special case of small-scale MRMC-WMNs, because all nodes are located in interference range of each other, Eq.13 is a necessary and sufficient condition. It is essential for any channel that $X^k \leq 1$ to have a collision free scheduling. Consequently, it is clear that $\bar{X} \leq 1$.

An important issue which we attempt to challenge here is the significance of load balancing on the channels. Some researches try to minimize the number of transmissions. Although this objective could improve the performance of WMNs, it is not sufficient. Based on the described model, First Rejected Session (FRS) happens once that airtime constraint is violated in any of the orthogonal channels. In order to maximize the feasible traffic load on the network (without any rejected session), it is essential to balance the traffic over all available channels. Thus, channel assignment strategy and broadcast routing should be designed such that minimize the variance of channel utilization. i.e. ,

$$\min \left(\frac{1}{K} \sum_{k=1}^K (X^k - \bar{X})^2 \right) \quad \text{S.T.} \quad \text{airtime constraint} . \quad (30)$$

To this end, we define “Traffic Engineering Efficiency” as follows:

$$\eta = \overline{NT} \frac{(FRS-1)T_0}{K c_0} \times 100\%. \quad (31)$$

Considering Eq. 29, it is clear that η shows the average utilization of channels before the first rejected session is happened. This is a useful parameter that indicates only the degree of channel load balancing for corresponding average number of transmissions. Certainly, It is desirable that firstly the number of transmissions be minimized and secondly $\eta = 100\%$. Whatever the load distribution on the channels is more uniform, the value of this parameter increases. In ideal case, for a certain amount of $\overline{NT}$, it is desirable that throughput tends to $K c_0 / \overline{NT}$.

VI. SIMULATION RESULTS

In this section, we study the accuracy of our analysis and obtained relationships by deriving some simulation results for two routing protocols: conventional Shortest Path Spanning Tree (SPST) and WCTB [7]. The number of transmissions produced by WCTB is very close to the optimal value [7]. It is considered as one of the best Minimum Number of Transmissions (MNT) protocols. Wireless systems normally support multiple channel rates. In the simulations, the channel rates 54, 36, 18, and 6Mbps are studied. For fixed transmission power of 6dBm, different receiver sensitivities (-65, -70, -77, and -82 dB, respectively), and using two ray ground propagation model, [14] derives communication ranges as 89, 119, 178, and 238m, respectively. As discussed in [14], interference ranges for different channel rates are very close to each other. Therefore, as well as other papers [13,14], for simplicity, it is assumed a single interference range of 480m for all rates. We consider bandwidth-guaranteed broadcast sessions where each one has 100kb/sec bandwidth requirement.

According to described model, we consider n mesh routers randomly distributed over a 350×350 m² area. In this paper, it is aim to analytically analyze the broadcasting performance. We are not looking for the best result. So, we use Random Channel Assignment (RCA) policy to assign channels to the links. The source of each broadcast session is selected randomly. Here, to avoid the isolated wireless nodes (especially for sparse networks), we regenerate the topology until a connected network is obtained. Each data point in the graphs is an average of 20 individual runs on different randomly experiments.

In the first set of simulations, assuming ($T_0 = 0.1$ Mb/Sec, $n=35$, $K=7$, $|NIC|=3$, and $n_s=FRS-1$), we study the accuracy of obtained relationships. Table.1 shows the results of this set of experiments. It is worth to note that according to parameters used in this scenario, the obtained results exactly follow our described analysis and proven relationships (Especially Eqs. 15, 26, and 29). This shows the validity of our analysis.

In the second scenario, we use 35 nodes equipped with 3 NICs in a 54Mb/sec network and change the number of orthogonal channels from 1 to 11. Fig. 1 shows the results of this set of experiments. Clearly, when we use only one channel, the efficiency of channel utilization is 100% but the throughput of the network is very low. The ability to utilize multiple channels substantially leads to more spectrum utilization and increases the actual bandwidth available to the network; therefore, the amount of interference in the network will be decreased and the throughput of the network will be increased. In practice, due to the lack of proper distribution of traffic on channels and the lack of suitable channel assignment strategy and also limitation of the number of channels, this process will be gradually saturated and can not follow ideal case. Thus, *Traffic Engineering Efficiency* will be decreased.

In next scenario, assuming three NICs per node and three orthogonal channels, we increase the density of nodes in a 54 Mb/sec network from 20 (as a sparse network) to 40 (as a dense network). The results are shown in Fig. 2. Obviously, by increasing the number of mesh routers in the network (denser network), the performance with respect to traffic engineering will be increased. On the other hand, since the

number of transmissions is increased, consequently the throughput of the network will be decreased.

In the last scenario, assuming 35 nodes equipped with 3 NICs, we investigate the effect of transmission rate on the FRS and the average number of transmissions. In general, higher transmission rate does not necessarily generate higher throughput. Due to rate-area trade-off, in higher rates, fewer nodes can be covered by a transmission. Thus, the number of transmissions will be increased. In contrast, the Transmission Time Fraction (TTF) [13] and implicitly the contentions will be decreased. As you can see from Fig. 3, in described model, the TTF reduction overcomes the increase of the number of transmissions; so that by increasing the transmission rate, FRS (and consequently throughput) is also increased. In addition, it is noticeable that by increasing the number of channels, the possibility of enjoying the WBA is decreased. So, the number of transmissions is increased but this process quickly saturated; on the other hand, the amount of interference in the network is also decreased. Thus, the FRS and throughput will be increased (Fig. 1a and Fig. 3a, b).

VII. CONCLUSION

Load balanced broadcast routing is one of the most challenging research issues in WMNs. In order to achieve the maximum feasible load in these networks, it is essential to balance the traffic over all available channels. In this paper, we studied the problem of traffic engineering in small-scale MRMC-WMNs. In this regard, by considering WBA and interference constraint, we derived analytical relationships between throughput, node utilization, number of transmissions and channel utilization. We also introduced the “*Traffic Engineering Efficiency*” to evaluate the quality of solutions obtained by any approximation algorithm.

TABLE 1. EXPERIMENT RESULTS OF THE FIRST SCENARIO

C_0 (M b/Sec)	RCA+Routing	$\bar{U}$	$\bar{X}$	$\bar{NT}$	FRS
54	MNT	0.097	0.57	22.09	98.8
	SPST	0.091	0.583	25.25	88.3
36	MNT	0.11	0.538	16.25	84.4
	SPST	0.098	0.555	20.3	69.8
18	MNT	0.14	0.494	10.4	60.8
	SPST	0.12	0.503	13.5	48.6
6	MNT	0.189	0.478	6.93	30.05
	SPST	0.169	0.489	8.2	26.3

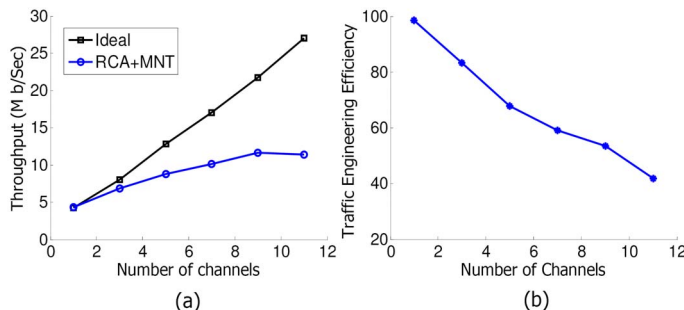


Figure 1. (a) Throughput and, (b) Traffic Engineering Efficiency as functions of the number of orthogonal channels

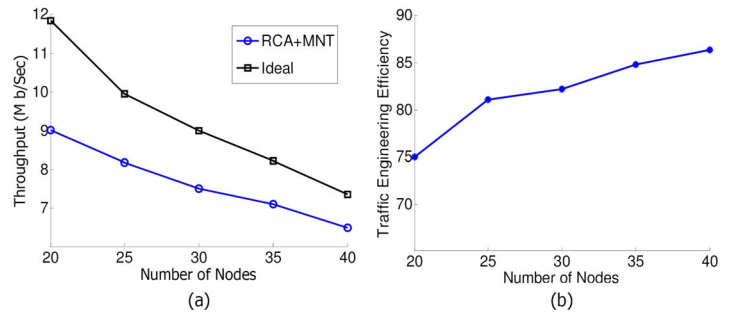


Figure 2. (a) Throughput and, (b) Traffic Engineering Efficiency as functions of the number of nodes

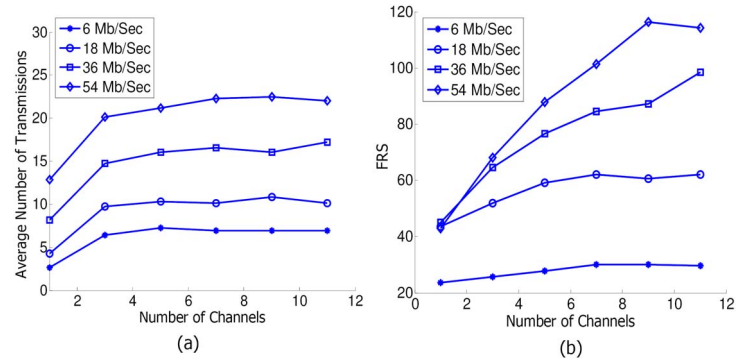


Figure 3. (a) Average number of transmissions, and (b) FRS as functions of the number of orthogonal channels and link layer transmission rate

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