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IEEE 802.16 Wireless Mesh Networks Capacity Assessment Using Collision Domains

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***Abstract*— Wireless Mesh Networks (WMN) are considered an attractive alternative to the traditional wired backbone networks for broadband Internet access. However, their capacity is limited due to the nature of the radio channel, which must be shared by the nodes forwarding the traffic from and to the gateway. Therefore, estimating the capacity of WMNs is an important question. The capacity analysis proposed for ad hoc networks can not be directly applied to WMN due to some fundamental differences, e.g. a different traffic pattern and node density. The main contribution of this work is the application of collision domains concept to the IEEE 802.16 based WMNs. We consider a simple chain topology but the method can be extended to any arbitrary topology and the real world impairments (interference, fading, etc.) can be easily incorporated in the analysis. The presented results may have important implications for 802.16 mesh networks planning.**

***Keywords*- capacity analysis; collision domains; IEEE 802.16; mesh network**

I. INTRODUCTION

Broadband wireless internet access is becoming more and more popular nowadays. This is especially true since the introduction of IEEE 802.16 standard for local and metropolitan area network, called WiMax, in 2001. However, all the deployed WiMax installations use point-to-multi-point (PMP) mode of operation. The revision of 802.16 standard published in 2004 specified an optional mesh mode, where the nodes operate not only as hosts but also as routers, forwarding packets on behalf of other nodes that may not be in the range of the base station. WMN may form a self-configured and self-organized wireless backhaul network, which can be deployed incrementally, one node at a time, as needed, replacing a more costly wired backbone. However, multihop wireless communication is a relatively new idea and requires much research effort to analyze and optimize its performance.

In this paper we will concentrate on capacity aspects of WMN [1], with special emphasis on 802.16 standard [2]. Recently, a lot of research has been carried out to investigate the capacity of ad hoc networks, but their results can not be directly applied to WMNs due to several reasons which will be explained in Section II. Section III shortly describes 802.16 MAC protocol and the specific features of the mesh mode of operation. In Section IV we will show how the concept of Collision Domains, presented by Jun et al. in [3], can be applied to 802.16 mesh networks to estimate the capacity. This will be followed by discussion of nominal and effective load of the 802.16 Collision Domains as well as construction of collision domains in multi-channel and multi-radio configurations. We will show numerical results obtained using the approach presented before and their verification by means of computer simulation in Section V. Finally, the work will be concluded in Section VI, where the possible directions for future work will be presented as well.

II. RELATED WORK

In the past decade a lot of research have been devoted to determining the capacity of wireless ad hoc networks. In the fundamental work by Kumar and Gupta [4] the analytical lower and upper bounds of stationary network capacity have been derived and it has been shown that the throughput capacity per node reduces significantly when the node density increases. In [5] the authors analyzed ad hoc networks allowing node mobility and showed, that, if long delays are tolerated, the capacity remains constant with the number of nodes. The other interesting results related to this work have been presented in [6] and [7].

However, most of the results valid for ad hoc networks can not be directly applied to mesh networks due to some fundamental differences. They have been identified in [3] and are discussed below:

A. In ad hoc network the traffic flows between any arbitrary pair of nodes while in WMN practically all the traffic is gateway oriented. WMN's BS acts as a hot spot and may be a bottleneck of the whole network's capacity.

B. Topology of the WMN is rather stable, with new nodes occasionally joining or leaving the network, while an ad hoc network can change dynamically in both, number of nodes and number of links/connections.

C. There are no energetic constraints, nodes have access to external power sources.

D. As a consequence of C. nodes can have multiple radios which can increase throughput capacity significantly.

E. The number of nodes and the required bandwidth in WMN may be higher than in ad hoc network.

F. Most of the results focused on the theoretical analysis for the asymptotic case. The resulting capacity bounds do not reflect the exact capacity of the WMNs with a given number of nodes.

Consequently, another methods of WMNs capacity estimation must be developed, which will be discussed in the next sections.

III. Overview of 802.16 Mesh MAC Protocol

The mesh mode of operation, introduced in 802.16d standard, is an important extension to the original PMP mode, with the advantage of less path loss, coverage and robustness improving exponentially as nodes are added to the network and larger user throughput over multi-hop paths [8], [9].

The TDMA MAC protocol designed for the mesh mode supports both centralized and distributed scheduling. In the centralized mode the mesh base station (BS), providing the connectivity to the wired backbone, is responsible for collecting bandwidth requests from subscriber stations (SS) and managing resource allocation. In the distributed mode, transmissions are scheduled in a fully distributed manner, without requiring any exchange of control information between the SS's and BS. Since decisions are taken locally by nodes, based on their current traffic load and channel conditions, the distributed mode is more flexible and responses quickly to the network requirements. Therefore, we will focus on the distributed mode only.

The TDMA frame structure used in the mesh mode is illustrated in Fig. 1. It is divided in the control and data sub-frames. The control sub-frame consists of 16 slots (transmission opportunities) and the data sub-frame is divided into multiple mini-slots. The control slots are accessed by nodes based on the distributed election procedure. Every node competes for the transmission opportunity using its neighbors' scheduling information and the procedure ensures that in a two-hop neighborhood there is only one node which can transmit its control message at a time.

The control slots are used to convey several types of control messages. Bandwidth negotiation is performed using MSH-DSCH (Mesh Distributed Schedule) message, which contains the schedule and data slots allocation of the broadcasting node and its neighbors. Consequently, each node can obtain scheduling information of its two-hop neighbors and data packet transmission is collision-free in the entire extended neighborhood. A three-way handshake procedure is used for data slot reservation. The negotiation phase consists of three steps:

1. the transmitting party sends out a request,

2. the receiving party responds with a grant,

3. the requester then confirms the indicated grant.

Such a mechanism is required since not all nodes are in the same transmission range in a mesh network [10].

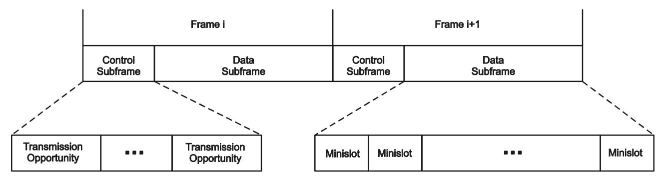

Fig. 1 IEEE 802.16 mesh mode frame structure.

IV. Collision Domains in 802.16 WMN

A. *Definition of collision domains in 802.16 WMN*

The concept of collision domains was applied to WMNs capacity calculation for the first time by Jun at al. in [3]. The method is based on the fact that the existence of gateways in WMNs introduces hot spots in the network that act as bottlenecks. Identifying the bottleneck collision domains allows computing exactly the minimum and maximum data rates available for each node for a given network topology and link layer protocol. The concept was further developed by Aoun and Boutaba in [11], by considering fairness to ensure proper operation of WMNs.

However, all the previously listed research considered 802.11 based WMNs only or did not take into account the specification of the MAC protocol at all. One of the key strength of the collision domains approach is the ability to include any MAC layer implementation by redefinition of collision domain. This is simply done by imposing a set of constraints (specified by the MAC protocol) on the links between nodes communicating in the mesh network.

The main contribution of this work is the application of collision domains concept to the 802.16 based WMNs, as specified in the 802.16 standard [2]. For clarity, let us consider a simple chain of $N = 8$ nodes (SSs) receiving and forwarding traffic from the gateway (BS). We will assume that the traffic is unidirectional (downlink), the bidirectional case will be treated later in Section VI. We define the collision domain CD_4 for link $k=4$ (between SS3 and SS4) as follows (see Fig. 2):

- the requester (SS3) broadcasts a *Request message*, notifying nodes SS2 and SS4 of its request – we include links 3 (SS2 → SS3), 4 (SS3 → SS4) and 5 (SS4 → SS5) in the collision domain CD_4,

- the receiver (SS4) responses with a *Grant message*, indicating the granted data slots to nodes SS3 and SS5 – we add link 6 (SS5 → SS6) to the collision domain CD_4,

- finally, we add link 2 (SS1 → SS2) to the collision domain CD_4, this step is done since node SS2 advertises its availability before node SS3 sends its grant confirmation (because of the cyclic way the control schedule is designed) and node SS1 is aware of the pending transmission in its extended neighborhood (and specifically between nodes SS3 and SS4),

- additionally, node SS1 will not accept any requests from BS (since SS1 is in the interference range of SS3) and, therefore, we add link 1 (BS → SS1) to the collision domain CD_4.

Unfortunately, the multi-hop hidden terminal problem has not been effectively eliminated in 802.16 MAC protocol. Referring again to Fig. 2, due to the uncoordinated channel access of node SS6, which is outside the extended neighborhood of node SS3 and may cause collisions at node SS4, we must include link 7 (SS6 → SS7) in the collision domain CD_4.

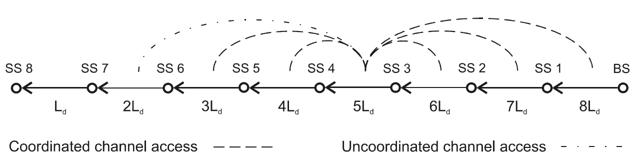

Fig. 2 Simple chain topology of WMN with 8 nodes.

B. *Nominal and effective load*

The definition of the collision domain presented in previous section allow us to compute the traffic to be forwarded within the collision domain. Assuming that each node in the chain (see Fig. 2) downloads from the gateway the traffic of $L_d\ [bit/s]$, a link which is closer to the gateway has to carry more traffic, e.g. link 1 (BS → SS1) has to carry the load of $8L_d\ [bit/s]$ while link 6 has to carry $3L_d\ [bit/s]$. Since each collision domain has to be able to forward the total load of its links, the collision domain CD_4 defined in the previous example forwards $8L_d + 7L_d + 6L_d + 5L_d + 4L_d + 3L_d + 2L_d = 35L_d$. If the bandwidth (the capacity of the MAC layer) for each link in the collision domain is constant and equal to $B[bit/s]$, the throughput L_d available to each node in the chain is limited to $L_d < B/35$ (for the considered collision domain CD_4). In order o find the collision domain which is limiting for the network (so called bottleneck collision domain) we have to identify the collision domain and its load for every link in the network and find the minimum throughput L_d [3].

The load of collision domain presented so far leads to a pessimistic value of the throughput L_d and is called the nominal load [11]. Instead, the effective load gives a more accurate estimate of the throughput by considering the spatial channel reuse, which is typical for multi-hop links in WMNs. Due to the spatial separation of links in the collision domain simultaneous transmissions are possible and should be deducted from the total load of the collision domain. Referring again to Fig. 2 we find out that link 2 (SS1 → SS2) can transmit simultaneously with link 6 (SS5 → SS6 - node SS2 is outside the interference range of node SS5) and we reduce the nominal load of collision domain CD_4 by the load of the lower loaded link in the pair. Similarly, link 1 (BS → SS1) can transmit simultaneously with link 5 (SS4 → SS5) and link 3 (SS2 → SS3) can transmit simultaneously with link 7 (SS6 → SS7). The effective load of the collision domain CD_4 is now equal to $35L_d - 4L_d - 3L_d - 2L_d = 26L_d$ and the throughput L_d available to each node in the chain is limited to $L_d < B/26$ (25% gain over the nominal load).

C. *Impact of link adaptation (MCS)*

The physical layer of 802.16 mesh mode is based on WirelessMAN-OFDM/TDD and features link adaptation (Modulation and Coding Scheme - MCS) for better utilization of radio resources [2]. Consequently, the raw data rates may vary from 2.40 Mb/s to 26.18 Mb/s (for 7 MHz channel), depending on the receiver SNR, which, in turn, is a function of propagation conditions as well as network topology.

With link adaptation every link in a specific collision domain may apply different MCS, which impacts the collision domain load – now the load of every link must be scaled by the inverse of its bandwidth. Let us consider a simple example of a WMN consisting of two SSs downloading equal traffic $L_d\,[bit/s]$ from the BS. Assuming identical bandwidth B for both links the collision domain load is equal to $L_d + 2L_d = 3L_d$ and the throughput L_d is limited to $L_d < B/3$. However, if the bandwidth of the link 1 (BS → SS1) is twice that of the link 2 (SS1 → SS2), i.e. $2B$, the load of the collision domain is calculated as $\frac{L_d}{1} + \frac{2L_d}{2} = 2L_d$ and the throughput L_d is now bounded by $L_d < B/2$.

Generally, for the collision domain CD_k including N_k links characterized by load L_i and bandwidth B_i the following equation must be fulfilled:

$$\sum_{i \in CD_k} \frac{L_i}{B_i} = 1$$

The quantity L_i/B_i defines the percentage of time available for link *i*, since the transmission time (in other words the available resources) must be shared among all links forming the collision domain to carry all its load.

D. Capacity increase in multi-channel mode

The 802.16 mesh MAC protocol is designed primarily for multi-hop networks operating in a single channel. However, the nodes can employ up to 16 multiple non-interfering channels [2] for data transmission to increase the available throughput for nearby nodes, which can not exploit spatial reuse. Assigning additional channels is known to be one of the most effective ways to increase WMN capacity [8].

The collision domain concept presented so far can be easily extended to incorporate the WMN operating in multiple channels. This requires re-defining collision domains, having in mind both the specific MAC protocol, as well as the existence of multiple frequency channels for parallel transmissions. Consequently, the construction of collision domains has to be performed for each specific channel assignment separately.

Let us refer to the example discussed in section IV.A. Assuming the specific channel assignment, as shown in Fig. 3, we can remove from the collision domain CD_4 (defined for link 4, which communicates over channel B) links 1 (BS → SS1), 2 (SS1 → SS2) and 6 (SS5 → SS6), since they use channel A and do not interfere with link 4 (SS3 → SS4). Although link 5 (SS4 → SS5) operates on channel A as well, it can not be removed from CD_4 due to the single-radio configuration of nodes (the node can not receive and transmit simultaneously). This reduces the nominal load of the collision domain CD_4 to $6L_d + 5L_d + 4L_d + 2L_d = 17L_d$. Taking into account spatial channel reuse, the effective load is further reduced to $17L_d - 4L_d - 2L_d = 11L_d$ (pairs 5-7 and 3-5 can transmit in parallel).

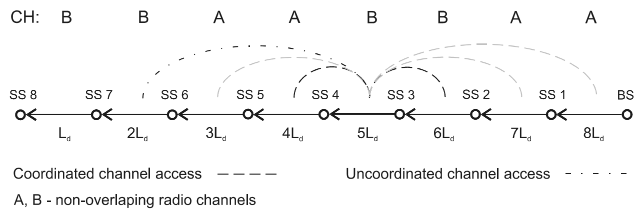

Fig. 3 Simple chain topology of WMN with 8 nodes configured in multi-channel mode.

E. Capacity increase with multi-radio nodes

As we could see in the previous section assigning additional channels to the link chain can substantially decrease the load of the collision domain, increasing the available throughput of the WMN. However, even if the number of available channels is very high, the collision domain can not contain less than three links in a single-radio configuration. This is caused by the fact that for a given link *i* both the transmitting node $i-1$ and the receiving node *i* can not receive (node $i-1$) nor transmit (node *i*) simultaneously with link *i*.

This limitation do not exist in a multi-radio configuration any more. Since cost of radios and battery consumption are not limiting factors in a WMN, multiple radios can be placed in nodes to increase the capacity of WMN.

Introducing multi-radio nodes releases the constraint limiting the capacity in multi-channel mode – now simultaneous reception and transmission (on different channels) is possible in every node. We refer again to the example discussed in section IV.A. If the specific channel assignment shown in Fig. 4 is applied, the collision domain CD_4 consists of links 3 (SS2 → SS3), 4 (SS3 → SS4) and 5 (SS4 → SS5), the nominal and effective load equals to $6L_d + 5L_d + 4L_d = 15L_d$ and $15L_d - 4L_d = 11L_d$, respectively in the single-radio configuration. By adding radios to nodes SS3 and SS4 the collision domain CD_4 reduces to the link 4 (SS3 → SS4) with load $5L_d$.

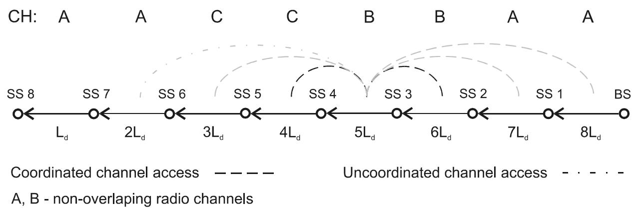

Fig. 4 Simple chain topology of WMN with 8 multi-radio nodes.

However, as we will see in the next section, multi-radio configuration requires a careful selection of channel assignment scheme to be really effective. When the number of channels is limited, multi-radio configuration may have no impact on WMN capacity in the worst-case scenario.

V. NUMERICAL RESULTS

A MATLAB® script was used to evaluate the method and we considered a chain topology similar to that presented in Section IV. The script identifies the collision domain for every link and calculates the available throughput. The results were verified using a custom-coded 802.16 mesh mode MAC simulator, written in C++.

A. Simple Chain Topology – Unidirectional and Bidirectional Traffic

Let us first analyze a single node downloading data from the gateway through a chain of forwarding nodes. Assuming the bandwidth B normalized to 1, the throughput available to the downloading node changes as $1/N$ for $N \le 4$, and reaches 0.25 for $N > 4$ (Fig. 5). The behavior is similar to 802.11 based chain [11], however, for 802.16 chain the nominal load of the bottleneck collision domain is $7L_d$ and the effective load is equal to $7L_d - 3L_d = 4L_d$.

If all nodes in the chain download the same traffic from the gateway the situation changes dramatically. In this case, for $N \ge 3$ the collision domain CD_4 (SS3 → SS4) is the most congested and forms a bottleneck. If the traffic is unidirectional (downlink or uplink) the throughput decreases to 0.1 (per node) for $N = 4$ and becomes as low as 0.03 for $N = 10$ (see Fig. 6). For bidirectional asymmetric traffic with $L_u = 0.1L_d$ (a value typical for ADSL links) the same throughput of 0.03 is reached for $N = 9$. If the traffic is symmetric ($L_u = L_d$), a similar throughput is obtained for $N = 6$.

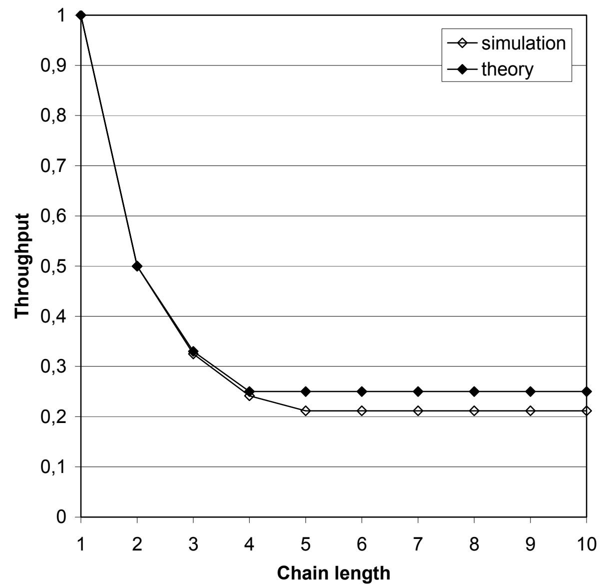

Fig. 5 Throughput vs. position of single downloading node.

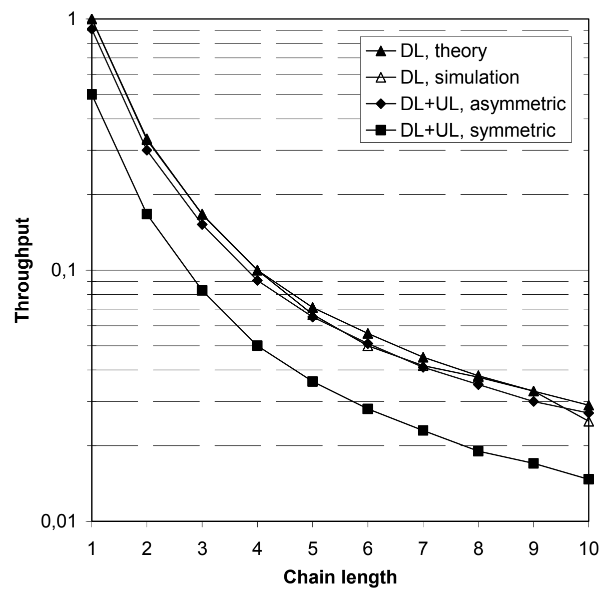

Fig. 6 Throughput vs. number of downloading nodes, unidirectional and bidirectional traffic.

The theoretical result for the downlink were compared against simulation and showed a good agreement (Fig. 6). However, the bidirectional case was not verified by simulation due to some limitations of the simulator, which currently supports unidirectional traffic only.

B. Effects of Adaptive Coding and Modulation

802.16 OFDM PHY layer used in the mesh mode features an adaptive coding and modulation scheme [10]. Using a modified version of the method presented earlier in this paper we can easily show the impact of the available bandwidth, which can vary from link to link, on the overall performance of the mesh network.

Doubling the bandwidth on the links 1 to 5 increases the throughput almost linearly (Fig. 7), however, modifying subsequent links does not increase it any more. The most important is the fact that the substantial change of the bandwidth impacts the location of the bottleneck collision domain, which can be observed by increasing the bandwidth of some links to $4B$. On the other hand, limiting the bandwidth to $B/2$ or $B/4$ on the links 1 to 4 decreases the throughput up to 57% and 85%, respectively.

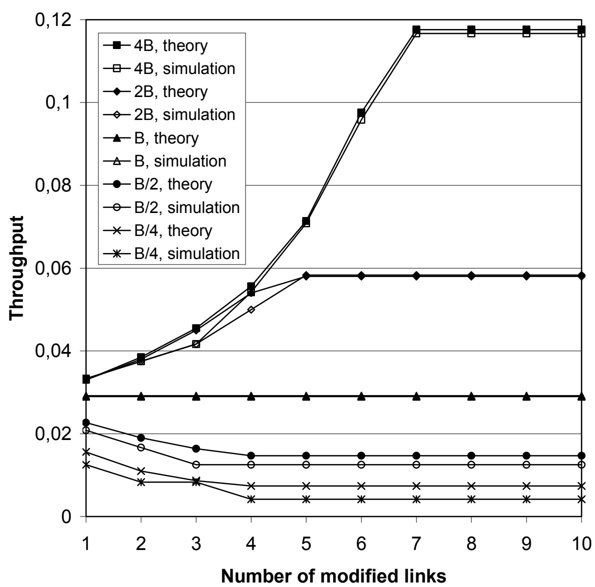

Fig. 7 Effect of adaptive coding and modulation – throughput vs. number of affected links in the chain.

From the above we can conclude that the performance of the 802.16 WMN depends heavily on the bandwidth available on the links closer to the gateway, while the bandwidth of the other links do not impact the performance of the network substantially.

Fig. 8 shows how the throughput is affected by changing the bandwidth of a single link in the chain. It should be noticed that the mesh network is more susceptible to the reduction of the bandwidth of the links than to its increase. This is important for 802.16 WMN planning, since the reduction of bandwidth of the links closer to the gateway reduces considerably the throughput available to all nodes. In the worst case scenario, limiting the bandwidth of link 1 to $B/2$ or $B/4$ decreases the throughput available to all nodes by 28% and 57% respectively.

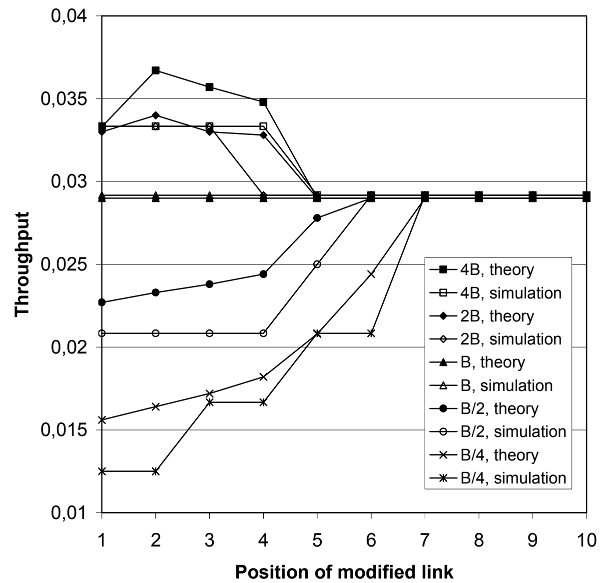

Fig. 8 Effect of adaptive coding and modulation – throughput vs. position of affected link in the chain.

C. Multi-channel mode

As mentioned in the previous section, assigning additional channels is one of the most effective ways to increase WMN capacity. However, networks exploiting multiple frequency channels require very careful selection of number of channels as well as their spatial configuration. We analyzed several configurations with 2, 3 and 4 channels, and some of the results are presented below.

A comparison of different channel assignment schemes in 2-channel configuration is shown in Fig. 9 and Fig. 10. From this figures we can find out, that the load of the collision domain is minimized (and the throughput maximized) when the channels alternate as often as possible (AABB – throughput increased by 100% for $N=10$), however, due to the limitations of the single-radio configuration the assignment ABAB should be avoided (see Fig. 11 and Fig.12).

Even if more channels are available for the 802.16 WMN at a given location, the throughput can be at most doubled in the single-radio configuration. The channel assignments schemes ABC and ABCD (Fig. 11 and

Fig. 12) as well as AABBCC (Fig. 13 and Fig. 14) performs identically as the previously analyzed AABB configuration. From this figures we can conclude, that in the simple 802.16 WMN chain and single-radio configuration the throughput can be doubled using 2 radio channels and assigning additional channels does not increase the throughput any more. However, the results may differ considerably for the WMN with more realistic (complex) topology and interference model and we plan to investigate the issue more deeply in the future.

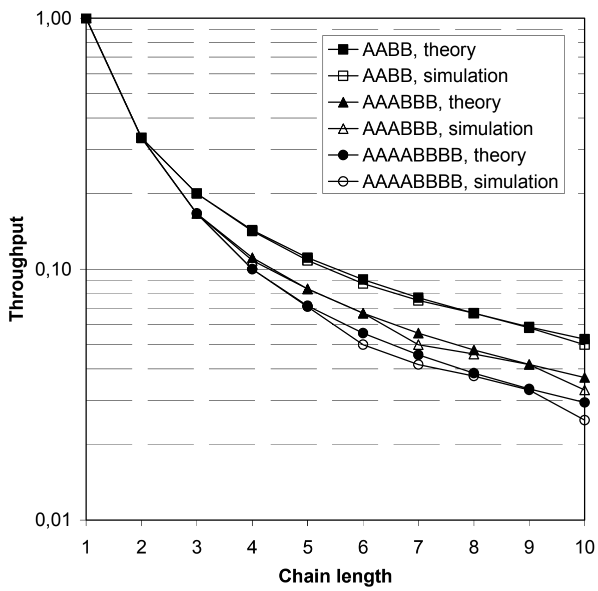

Fig. 9 2-channel configuration – comparison of 3 possible channel assignment schemes.

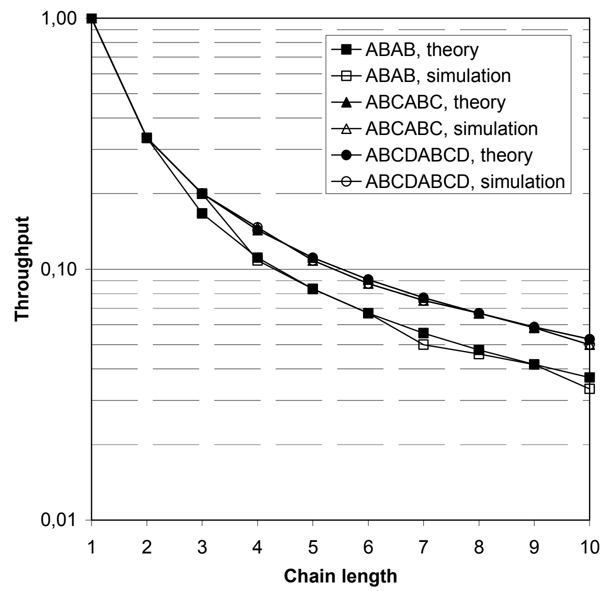

Fig. 11 Comparison of 2, 3 and 4 channel configurations.

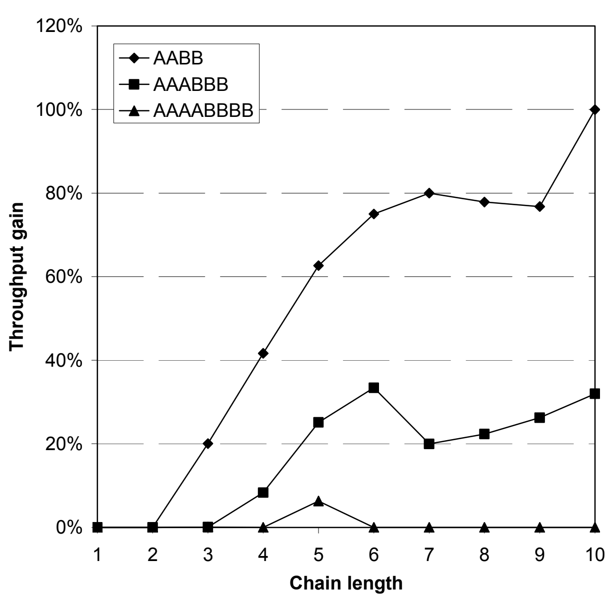

Fig. 10 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 9.

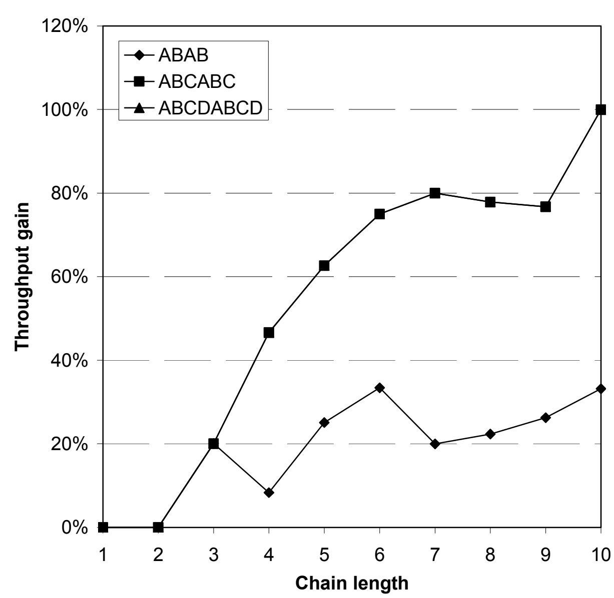

Fig. 12 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 11

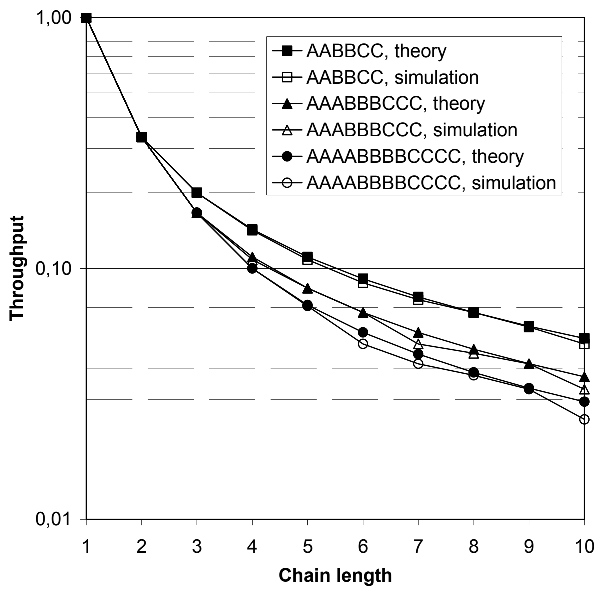

Fig.13 3-channel configuration – comparison of 3 possible channel assignment schemes.

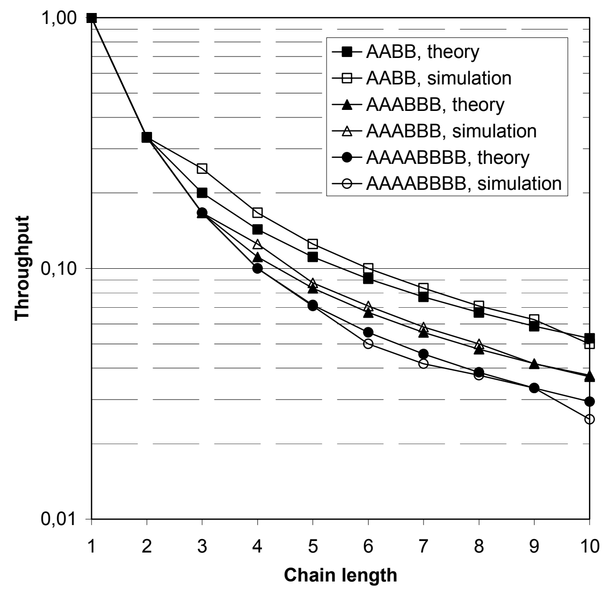

Fig. 15 Multi-radio configuration and 2-channel assignment schemes.

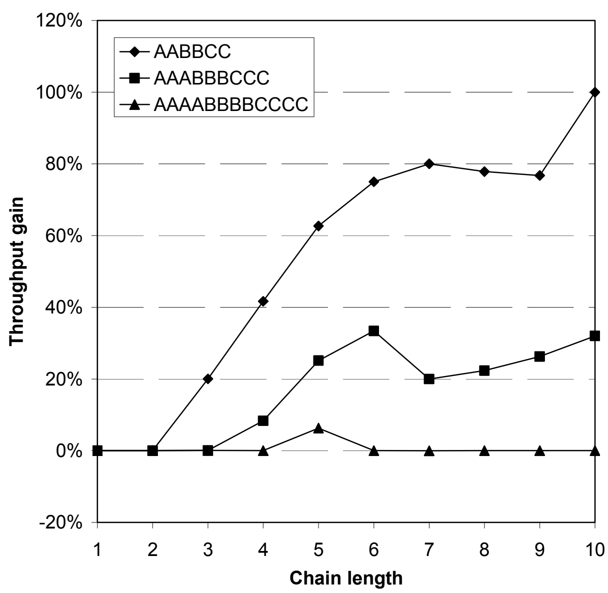

Fig. 14 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 13

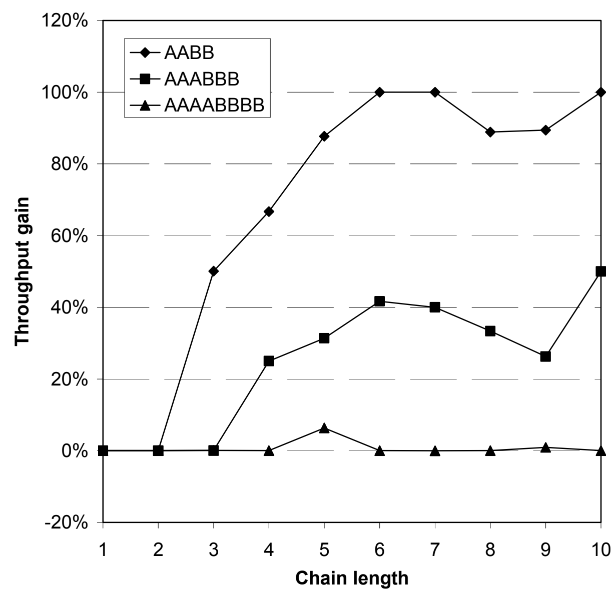

Fig. 16 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 15.

D. *Multi-radio configuration*

The further reduction of 802.16 collision domains load, resulting in the increased throughput, requires introducing multi-radio nodes in the network. As argued in Section IV.E the collision domain can be reduced to the single link with the sufficient number of radio channels in this case.

With two radio channels available to the WMN the throughput can be increased by 100% (Fig. 15 and Fig. 16) in the multi-radio configuration. We obtained similar results in the single-radio configuration, however with multi-radio nodes the throughput is doubled for shorter chains, i.e. 6 nodes vs. 10 nodes in multi-channel case.

The advantages of the multi-radio configuration are fully exploited when more than two radio channels are available (Fig. 17). Adding one channel increases the throughput by 130% for N=10 (ABCABC - Fig. 18), while four fold (300%) increase is observed for the 10-node chain configured with four channels (ABCD).

A comparison of 3-channel multi-radio configurations is presented in Fig. 19 and Fig. 20. Unlike the single-radio configurations, adjacent links should avoid operating in the same channel since the multi-radio nodes can receive and transmit simultaneously, if assigned non-interfering channels.

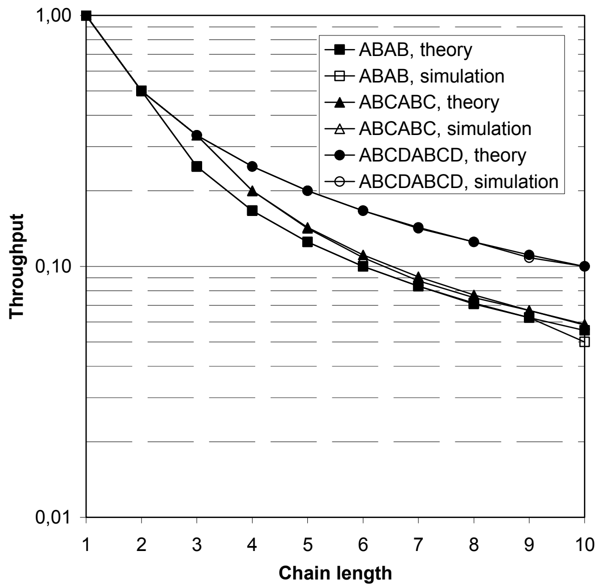

Fig. 17 Comparison of 2, 3 and 4 channel configurations with multi-radio nodes.

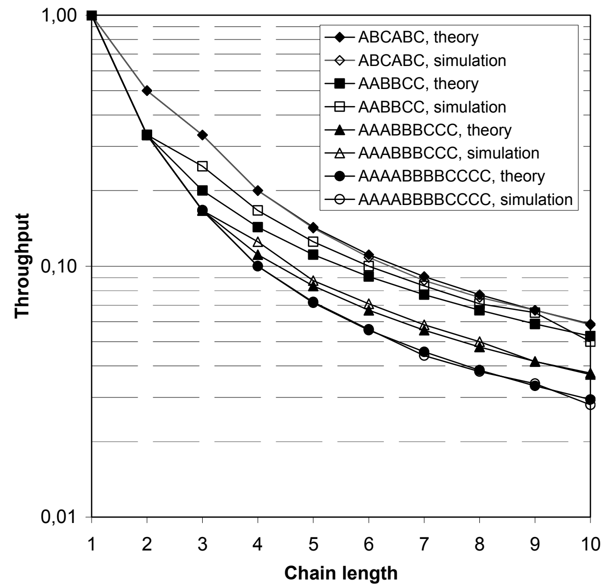

Fig. 19 3-channel configuration – comparison of 3 possible channel assignment schemes.

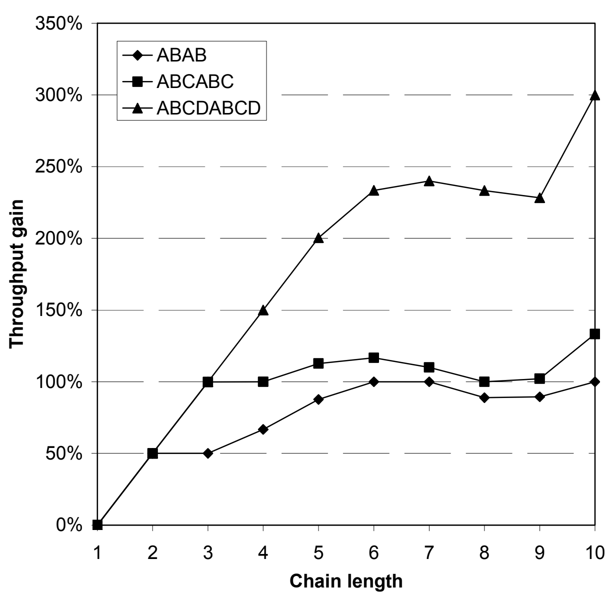

Fig. 18 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 17.

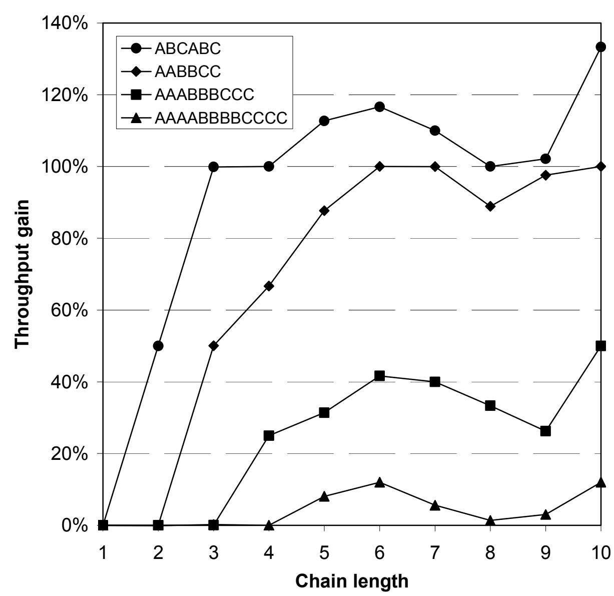

Fig. 20 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 19.

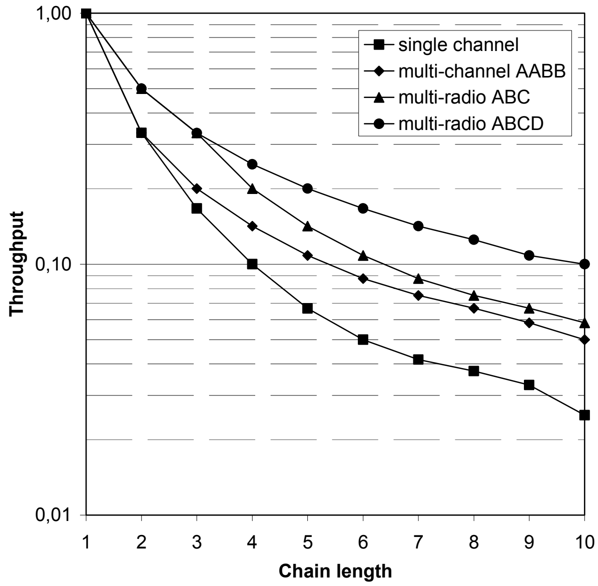

Fig. 21 Comparison of selected multi-channel an multi-radio configurations of the 802.16 WMN.

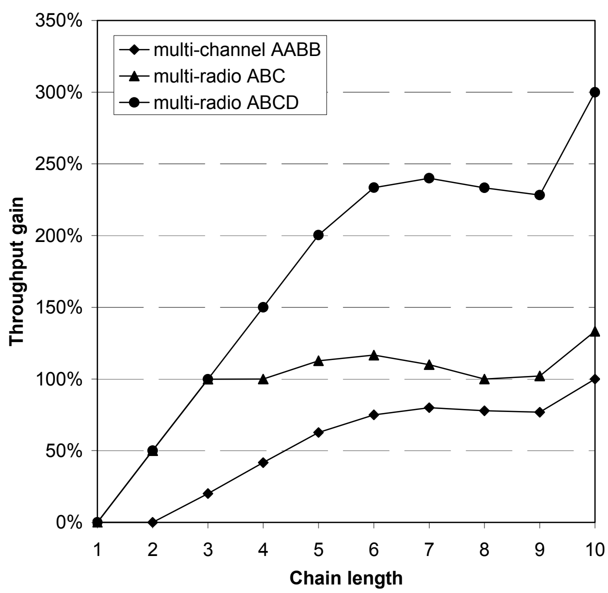

Fig. 22 Throughput increase (relative to the single channel) for the channel assignments shown in Fig. 21

Fig. 21 and Fig. 22 summarize the benefits of the multi-channel and multi-radio modes of operation of the 802.16 WMN. We can see from these figures that the simplest but effective method of increasing the throughput requires adding the additional (and properly configured - AABB) radio channel. The further throughput increase is possible by assigning another channels (ABC, ABCD) and replacing single-radio nodes by multi-radio devices.

VI. CONCLUSION

In this paper we showed how the concept of collision domains can be applied to 802.16 WMN capacity calculation. The definition of collision domain is strongly affected by the MAC protocol used. Therefore it must be redefined for every mesh network standard.

The collision domain concept proved to be exact, the results obtained by simulation of the 802.16 MAC layer are close to the theoretical analysis based on collision domains. We extended the method by allowing the variable bandwidth of each link, implemented in the 802.16 standard by the application of adaptive coding and modulation. The other extensions, like multi-channel and multi-radio terminals were included as well. The results obtained using the modified method may have important implications for WMN planning.

However, the simple chain topology and the unrealistic interference model considered throughout the paper does not allow for any generalization of the results. We plan to adapt the method to the arbitrary topology of the 802.16 WMN. Since the collision domains are defined based on the interference among links, this can be done only after implementation of the more realistic propagation models in our collision domain identification algorithm.

Finally, the mesh mode is very likely to be replaced by the relay solution in the new version of the 802.16 standard. Therefore, we will consider the application of the collision domain concept to the new mode as well as to the forthcoming IEEE 802.11s standard.

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