Partially Overlapped Channel Assignment on Wireless Mesh Network Backbone

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***Abstract*—The Wireless Mesh Network (WMN) has already been recognized as a promising technology as broadband access network from both academic and industry points of view. In order to improve its performance, researchers have investigated how to increase the number of simultaneous transmissions in the network while avoiding signal interferences among radios. Considering WMNs based upon IEEE 802.11 b/g standards, lately most researchers have been relying on the usage of orthogonal channels for solving the Channel Assignment (CA) problem. In this paper, we introduce a novel CA algorithm exploiting partially overlapped channels (POC) that overcome the common orthogonal channel approach and also a recently proposed CA algorithm using POC.**

I. Introduction

WMNs have attracted an immense interest from researchers, industry, and users. WMNs are considered to be a key technology in Next Generation Networks and aims at deploying ubiquitous Internet access. With such a promising future, several standards have been developed for different access ranges, namely IEEE 802.15.4, IEEE 802.11s, and IEEE 802.16j. This paper focuses on WMNs based on WLAN technology, i.e. IEEE 802.11s.

WMNs consist of a multi-hop environment. However, its concepts and targets differ from those of conventional Mobile Adhoc Networks (MANETs). A WMN comprises two different types of nodes, namely Mesh Routers (MRs) and Mesh Clients (MCs). The former is responsible for network routing and bridging while the latter, being a light-weight node, would perform, if necessary, just the routing function. Moreover, MRs compose a backbone network, and concerning mobility and battery life-time, they are usually static and have no constraints on energy consumption. Such differences between WMNs and MANETs lead to novel protocols development to deal with specific challenges on WMNs.

In WMNs, several solutions have been already proposed to improve their capacity, such as modified Medium Access Control (MAC) protocols, directional and Multiple Input Multiple Output (MIMO) antennas and Multi-Radio Multi-Channel (MRMC) topology. Inside the MRMC field, one of the most promising techniques is Partially Overlapped Channel Assignment by using IEEE 802.11 b/g devices that can increase the network throughput by exploiting more simultaneous transmissions. According to the afore-mentioned standard, there are 11 channels available to communication on the 2.4 GHz ISM band. Each of them has a bandwidth of 22 MHz and a center frequency distance of only 5 MHz. Hence, there are just three orthogonal channels available, namely, channels 1, 6 and 11. Using these three channels configuration does not provide an efficient frequency-spatial reuse. However, by exploiting all 11 channels in a systematic approach to avoid the interference among adjacent channels, we are able to achieve a greater number of simultaneous transmissions. Nevertheless, this systematic approach is not trivial, and if not well planned, it may severely degrade the network throughput and delay due to adjacent channel interference, which is significantly more harmful than the co-channel interference.

The remainder of this paper is organized as follows. Section II surveys related works on solving MRMC CA problem, followed by Section III which reviews the interference model used for this article. Section IV describes our novel CA mechanism. Its performance is evaluated in Section V by comparing it against conventional algorithms. Finally Section VI concludes the paper.

II. Related Works

A multi-channel MAC (MMAC) protocol for handling multi-channel assignment using a single radio was proposed in [1]. The protocol uses non-overlapping channels and it reserves one channel for control packets and two others for data packets. Draves *et al.* [2] start employing multi-radio topology. In their contribution, a new routing metric called WCETT was developed. In their work however, they assumed non-interfering channels and employed fixed CA.

In 2007, a survey on channel assignment was performed by Skalli *et al.* [3]. Including the surveyed and proposed algorithms, all of them employ non-overlapping channels. According to this paper, “this leads to efficient spectrum utilization and increases the actual bandwidth available to the network”.

More recently, Bukkapatanam *et al.* [4] using numerical analysis showed that the usage of overlapping channels achieves better performance than three non-overlapping channels in the WMN backbone, expanding the previous work of Mishra *et al.* [5], [6]. However, none of the three above cited works actually describes a novel CA algorithm exploiting Partially Overlapping Channels (POCs).

Following the promising trend of using POC, a new CA algorithm was proposed in [7]. However, that algorithm does not take into consideration several key concepts considering the WMN multi-hop topology. Firstly, the algorithm starts assigning channels to nodes arranged in descending order of number of links to neighbors (i.e., node degree). This methodology may not protect the most sensible area of a

WMN, namely the gateway connection to the Internet. Since most of the traffic in such kind of an access network is directed to the Internet rather than neighbor communication, this algorithm may cause a very problematic bottleneck around the gateway. In our algorithm, as it will be explained in details later on, instead of ordering the CA precedence by node degree, we order all links in descending order of traffic load, consequently the busiest link is the first one to be assigned a channel, and so on. The advantages of this approach are two fold. First, it prioritizes the links around the gateway. Second, it leads to a better network connectivity. Also, unlike the work in [7], when all possible non-interfering links were assigned, we may still have some radios that were not assigned any channel due to interference constraints. In our algorithm we address these remaining radios to frequencies that will cause just co-channel interference. The reason behind this is the fact that simultaneous transmissions in the same channel may be considered less harmful than adjacent channel interference. This is due to the fact that MAC protocol (CSMA/CA) during a transmission attempt would recognize the medium as busy, which would not happen for adjacent channels leading to signal interference and packet collision.

III. Interference Model

We may define the CA as an optimization problem in terms of mapping available communication channels to network interfaces in order to maximize the communication capacity while minimizing signal interference.

Interference range is defined as the distance within interference occurs. In a multi-channel environment, four different types of interference and their influence on the network capacity should be addressed. Consider two pairs of nodes, each of them having a sender and a receiver. Let the senders be denoted by S_1 and S_2, and let the receivers be referred to as R_1 and R_2. All nodes are positioned within the interference range.

- Co-channel Interference: It occurs in case that all four nodes are operating in the same channel. Because of CSMA/CA, this type of interference is less harmful for the network capacity than Adjacent Channel Interference (ACI). Consider the following scenario: node S_1 is starting to transmit a packet to R_1. It checks whether the medium is busy or idle. If it is busy, the node will withdraw its transmission and postpone it. However, if the medium is idle, it will proceed with the transmission. Meanwhile S_1 is sending data to R_1, S_2 also attempts to send a packet to R_2. S_2 will follow the same medium detection procedure. In this case, the medium will be busy. Hence, S_2 will withdraw the transmission attempt and wait over a backoff period. Later on, it will attempt again and the transmission between S_1-R_1 will be already ceased. Then, S_2 will detect the medium as idle and finally succeed in transmitting the signal. In this scenario, we have a contention based access, in which a concurrent access to the medium occurs.
- Orthogonal Channels: In this scenario interference will not occur. Consider S_1-R_1 and S_2-R_2 using two orthogonal channels. Again, S_1 detects an idle medium and starts the packet transmission. Meanwhile, S_2 will also detect an idle medium since it is operating on a distinct channel. Both pairs successfully transmit their packets, because there is no overlapping frequency band between those channels.
- ACI: This kind of interference seriously degrades the network capacity. Consider S_1-R_1 and S_2-R_2 assigned to channels 1 and 3, respectively. Following the previous scheme, S_1 begins transmitting first, S_2 will detect an idle medium in channel 3 and also start to send its packets. However, since channels 1 and 3 share frequency band, the receivers will not be able to decode the packets, causing a transmission error that severely degrades the network throughput.
- Self-interference: Self-interference is defined as a node causing interference to one of its own transmissions. This case will occur in multiple radio nodes using omnidirectional antennas. Consider S_1 with two network interfaces. If one interface is assigned to channel 1 and the remaining one belongs to channel 3, whenever S_1 tries to simultaneously send packets on both interfaces, the SIR (Signal to Interference Ratio) will be degraded no matter where the receiver node is. This type of interference was previously mentioned in [8] and it can be avoided if no node has its interfaces assigned to overlapping channels.

Considering the afore-mentioned types of interference, the authors in [7] developed a schematic procedure for CA. This model is called as I-Matrix and it determines whether it is possible or not to assign channels to a given link exploiting POC. To adopt this model, we need to define four key components, namely Interference Factor, Interference Vector, Interference Matrix, and finally Threshold Interference.

A. Interference Factor

TABLE I: Interference Range (IR)

δ	0	1	2	3	4	5
$IR(\delta)$	13.26	9.08	7.59	4.69	3.21	0

The *interference factor* $f_{i,j}$ takes as input parameters geographical distance and channel separation, and provides the effective spectral overlapping level between channels i and j.

In order to calculate $f_{i,j}$, the experimental measurements showed in [8] [9] are used. To achieve an environment as similar as possible to the previous CA scheme, we use the same *Interference Range* (IR) table where δ is the channel separation $\delta = |i - j|$ and $IR(\delta)$ is the maximum distance in which there will be interference between channels i and j.

Given the IR table, let d be the Euclidean distance between transceivers using channels i and j. Also, if transceivers are in the same node, we define d being zero. To calculate $f_{i,j}$ we should consider the following three cases:

1) $f_{i,j} = 0$: when $\delta > 5$ or $d > IR(\delta)$

TABLE II: Interference Matrix

	d_i	*CoC*	*Ch1*	*Ch2*	*Ch3*	*Ch4*	*Ch5*	*Ch6*	*Ch7*	*Ch8*	*Ch9*	*Ch10*	*Ch11*
Ch1	d_1	0/1	$f_{1,1}$	$f_{1,2}$	$f_{1,3}$	$f_{1,4}$	$f_{1,5}$	0	0	0	0	0	0
Ch2	d_2	0/1	$f_{2,1}$	$f_{2,2}$	$f_{2,3}$	$f_{2,4}$	$f_{2,5}$	$f_{2,6}$	0	0	0	0	0
Ch3	d_3	0/1	$f_{3,1}$	$f_{3,2}$	$f_{3,3}$	$f_{3,4}$	$f_{3,5}$	$f_{3,6}$	$f_{3,7}$	0	0	0	0
Ch4	d_4	0/1	$f_{4,1}$	$f_{4,2}$	$f_{4,3}$	$f_{4,4}$	$f_{4,5}$	$f_{4,6}$	$f_{4,7}$	$f_{4,8}$	0	0	0
Ch5	d_5	0/1	$f_{5,1}$	$f_{5,2}$	$f_{5,3}$	$f_{5,4}$	$f_{5,5}$	$f_{5,6}$	$f_{5,7}$	$f_{5,8}$	$f_{5,9}$	0	0
Ch6	d_6	0/1	0	$f_{6,2}$	$f_{6,3}$	$f_{6,4}$	$f_{6,5}$	$f_{6,6}$	$f_{6,7}$	$f_{6,8}$	$f_{6,9}$	$f_{6,10}$	0
Ch7	d_7	0/1	0	0	$f_{7,3}$	$f_{7,4}$	$f_{7,5}$	$f_{7,6}$	$f_{7,7}$	$f_{7,8}$	$f_{7,9}$	$f_{7,10}$	$f_{7,11}$
Ch8	d_8	0/1	0	0	0	$f_{8,4}$	$f_{8,5}$	$f_{8,6}$	$f_{8,7}$	$f_{8,8}$	$f_{8,9}$	$f_{8,10}$	$f_{8,11}$
Ch9	d_9	0/1	0	0	0	0	$f_{9,5}$	$f_{9,6}$	$f_{9,7}$	$f_{9,8}$	$f_{9,9}$	$f_{9,10}$	$f_{9,11}$
Ch10	d_{10}	0/1	0	0	0	0	0	$f_{10,6}$	$f_{10,7}$	$f_{10,8}$	$f_{10,9}$	$f_{10,10}$	$f_{10,11}$
Ch11	d_{11}	0/1	0	0	0	0	0	0	$f_{11,7}$	$f_{11,8}$	$f_{11,9}$	$f_{11,10}$	$f_{11,11}$

In this case, there will be no interference between the radios since either they are assigned orthogonal channels, or they are distant enough not to cause interference given IR for channels i and j.

2) $1 < f_{i,j} < \infty$: when $0 \leq \delta \leq 5$ and $d \leq IR(\delta)$
Here, we have two radios assigned to overlapping channels i and j, also the distance between them is within the interference range. Thus, interference factor should be calculated as the following equation in which $f_{i,j}$ is inversely proportional to the distance between radios.

$$f_{i,j} = IR(\delta)/d : \qquad (1)$$

3) $f_{i,j} = \infty$: when $0 \leq \delta \leq 5$ and $d = 0$
Here, we strictly exclude the self-interference to occur. Overlapping channels will not be assigned at a given node.

B. Interference Vector

For a given channel i, we should calculate the Interference Factor between this channel and all other 11 channels. Note that here, the distance d_i stands for the closest radio at channel i. In order to permit the co-channel assignment, we add Co-channel (CoC) column in the I-Matrix. This value will be set to one, if the channel assigned to that radio is an interfering co-channel, or to zero, otherwise.

C. Interference Matrix

After combining the interference vectors for all 11 channels, the I-Matrix is formed, as shown in Table II. Each node has its own I-Matrix. Initially, all entries are set to zero and after a channel is assigned for any given link, every node updates its I-Matrix.

D. Threshold Interference

Setting this parameter on a value $(Th < 1)$, only non-interfering channels will be assigned. The tolerance for interfering links can be increased specifying $(Th > 1)$. Increasing this parameter's value would lead to a more connected network. However those links would suffer with ACI. In our algorithm, we increase the network connectivity exploiting the links that cause co-channel interference.

IV. Envisioned Algorithm

There are two main components in our envisioned algorithm, namely the network traffic load and the I-Matrix. The former is calculated beforehand and used as an input file to the algorithm. This component's purpose is to describe which links should be assigned channels and, most importantly, in which priority this should occur. The latter is initially set to zero and is used as a systematic method to assign channels to the links assuring that interference will not happen until the possibility of using non-interfering links is exhausted. By exploiting the I-Matrix in a unique manner, we cover disconnected nodes, connecting them to the network in such a fashion that the disconnected node will connect to a neighbor using one of the channels already assigned to the neighbor, as long as it does not cause self-inteference.

Using the network traffic load as input, the algorithm order the links in descending order of traffic. For each link, it consults the information on I-Matrix from both incident nodes and then tries to assign a suitable channel. This strategy was chosen to protect the most sensible part of the network, namely the gateway connection to the Internet, since most of the traffic in a WMN is directed to the Internet rather than the nodes with maximum number of links, that not necessarily, would have intense traffic load. For example, let two nodes u and v be connected by a link e. For assigning a channel c for e, the algorithm will compute the total channel interference on the channel c for all 11 channels. Whichever channel gives the smallest value will be pre-selected. If the total channel interference on the pre-selected channel is less than the threshold (Th), then the channel is assigned to the link e.

Immediately after the channel assignment, in each node, the Interference Vector in the I-Matrix corresponding to the assigned channel is updated. The distance d_i between the node and the closest from u or v is calculated and the Interference Factor for channel c is updated as follows, according to the clauses in Sec. III.

$$f_{c,i}^{new} = f_{c,i}^{prev} + f_{c,i}, \quad 1 \leq i \leq 11 \qquad (2)$$

At this point of the algorithm, all non-interfering links are already assigned. However, the full network connectivity is not yet accomplished. So, as a second phase, the algorithm detects the lists of nodes that do not have a routing path to the gateway. Such lists can be composed by one node, if the node's network interface was not assigned any channel due to interference restriction, or multiple nodes that already have some links between themselves. However, none of them can establish a path to the gateway. One node in each list should have one of its remaining interfaces assigned to the same channel as one of its neighbors that is already indirectly connected to the gateway. By employing such a scheme, we guarantee full network connectivity at the cost of few links in the network having co-channel interference. Those links, as will be shown in simulation results in Sec. V, do not strongly influence the network performance. In order to increase the connectivity, increasing the Th value may also be a viable option. However, this choice would definitely impact more the network performance, since adjacent channel interference would degrade SIR at the receiving node because both links would have channels with overlapping frequency and $IR(\delta)$ would not be distant enough. The pseudo-code of our envisioned algorithm is shown below.

Algorithm 1 Channel Assignment (CA)

```
foreach link e in sorted list do
    ch ← Get_Channel(e)
    if ch = Valid Channel then
        e.Assign_Channel(ch)
        for all nodes: Update I-Matrix(ch)
    else
        cannot assign channel
    end if
foreach end
foreach node list L not connected to Gateway (GW) do
    order nodes in ascending order of hops to GW
    foreach node n ∈ L do
        foreach link e ∈ n do
            ch ← Get_CoChannel(e)
            if ch = Valid Channel then
                e.Assign_Channel(ch)
                for all nodes: Update I-Matrix(ch)
            else
                cannot assign channel
            end if
        foreach end
    foreach end
foreach end
```

Algorithm 2 Get_Channel(e)

```
Get adjacent nodes of link e: n1 and n2
min ← ∞
for ch_i ← 1, 11 do
    Calculate total I-Factor for ch_i on n1 and n2
    if min > n1.total_ifactor(ch_i) + n2.total_ifactor(ch_i) then
        min ← n1.total_ifactor(ch_i) + n2.total_ifactor(ch_i)
    end if
    if min < Threshold_Interference then
        return ch_i
    end if
end for
```

Algorithm 3 Get_CoChannel(e)

```
Get adjacent nodes of link e: n1 and n2
# n1 (connected to GW), n2 (not connected to GW)
Get array of channels used by n1 and n2: ch1[] and ch2[]
foreach channel i in ch1[] do
    foreach channel j in ch2[] do
        if |i − j| ≥ 5 then
            return i
        end if
    foreach end
foreach end
```

V. Performance Evaluation

In this section, we evaluate the former CA scheme that we will call from now on as "original" and our new proposed CA that we will refer to as the "proposed" one . We simulate both algorithms in a network simulator widely used in the academic environment.

A. Simulation Environment

The simulation scenario was configured in Network Simulator (NS-3.6) as follows. A grid topology is constructed on the backbone. The grid step is set to 12 m, which is the distance between adjacent nodes. The node positioned in the bottom right corner is assumed to be the gateway. IEEE 802.11g is used as the wireless technology. MCS 6 Mbit/s is set as link data rate. In our experiments, we vary the grid size using 3x3, 3x4, 4x4, 4x5, and 5x5 arrangements that we will refer to as 9, 12, 16, 20, and 25 topologies, respectively.

B. Algorithm Evaluation Metrics

Regarding the evaluation metrics, we use the number of non-interfering links assigned to a given topology. We also use as metrics, the number of nodes connected to the gateway. And finally, the network throughput measured at the gateway.

C. Node Degree and Connectivity

In the first evaluation in Fig. 1, we intended to measure if the different strategies of CA, node degree or link load, would degrade the network performance. In other words, we focus on how many non-interfering links each strategy is able to assign. Our purpose here is to verify if our algorithm underperforms compared to the previous one regarding the number of links assigned considering an identical environment. As a result, we obtain that both of them have almost the same performance. Hence, the number of simultaneous communication in the network, and consequently the theoretical network capacity, can be considered equivalent. It is worth mentioning that because of the short inter-channel spacing in IEEE 802.11g, it is virtually impossible to assign just non-interfering links for all the nodes in every possible topology.

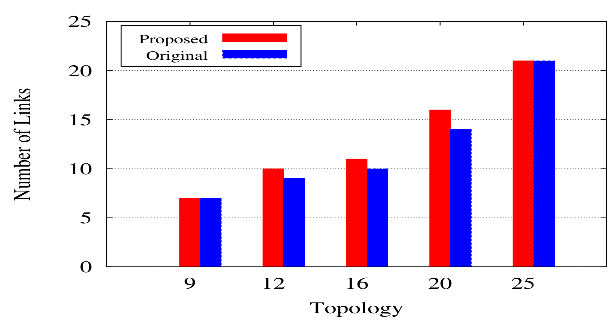

Fig. 1: Link Assignment.

The second evaluation metric is considered vital for the perfect deployment of any WMN, *i.e.* connectivity. Here, we measure the number of nodes that are able to send and receive packets from the network gateway. The shortcoming of the "original" algorithm is apparent here. Although many non-interfering links are assigned, network connectivity is not well addressed. Our algorithm greatly deals with this important issue by ensuring a connected path from all nodes to the gateway. Although not expressed in Fig. 1, it is important to highlight that the strategy of assigning channels to the links with heavier traffic loads guarantees good connectivity of the nodes closer to the gateway, since those links are addressed firstly. As a consequence of this fact, most of the disconnected nodes are positioned at the grid extremities and distant from the network bottleneck.

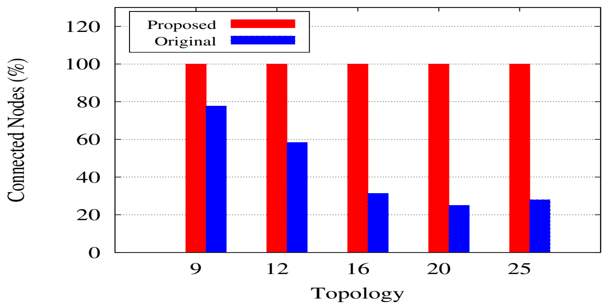

Fig. 2: Network Connectivity.

D. Throughput

Also, we evaluate the impact of using co-channel interference links. For this experiment we set our simulation environment as follows. Each node in the grid is able to communicate to its one hop neighbors except for the diagonal neighbors. It means that the center node is able to successfully communicate with the right, left, upper, and bottom nodes. Each node generates a Constant Bit Rate (CBR) traffic towards the gateway. The data rate is set to $(i * Throughput/(NumNodes - 1))$. This means, for example, in a grid topology of 3x3 nodes, we would have 8 nodes generating the traffic and the maximum throughput on the gateway, with two possible connections to its neighbors, would be twice the nominal throughput of each interface. In short, the CBR rate will be $2*6Mbps/(9-1) = 1.5Mbps$.

This traffic rate should ideally guarantee that each node in the experiment is able to have a reserved bandwidth on the gateway, avoiding the packets not to reach the gateway because of resource starvation (bandwidth) caused by nodes closer to the gateway. Moreover, this experiment's design also evaluates, as an additional result, how balanced the paths from the nodes to the gateway are. In other words, if most of the nodes access the gateway through the same interface, the amount of traffic coming to this interface will exceed the maximum throughput capacity while the other interface will be running under its maximum bound, since too few packets will be arriving at this interface. In Fig.3, the maximum throughput is set for the real throughput achievable in the application layer other than the nominal capacity of the physical layer.

In Fig. 3 in order to compare our results, we also add one more CA protocol, called Hybrid Multi-Channel Protocol (HMCP) [10], which uses non-overlapping CA. Briefly, in HMCP each nodes uses two radios to communicate. Each radio has different tasks to perform. The first radio uses a fixed channel and is responsible for receiving data while the second radio has a switchable nature since it changes its communication channel to reach the neighbors' fixed radios.

As demonstrated by Fig. 3, our CA performs close to the maximum limit. In addition, it can also be noticed that the

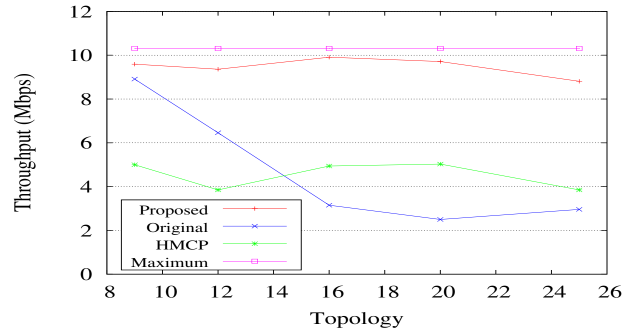

Fig. 3: Gateway Throughput.

occurrence of co-channel interfering links do not severely impact the network throughput. This happens because of two reasons. First, this type of interference is well addressed by the CSMA/CA MAC protocol. Second, our CA scheme tends to avoid its occurrence near the network bottleneck, where the traffic load is heavy.

VI. Conclusion

In this article, we developed a new CA algorithm for WMNs. In our algorithm, we exploited partially overlapping channel assignment following the latest research trends in the field. From the simulation results and analysis, we conclude that, overlapping channels can overcome the overall performance of the orthogonal CA strategies. As future directions, we plan to numerically evaluate our proposed algorithm's performance by considering a theoretically optimal CA.

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