Towards Centralized Spectrum Allocation Optimization for Multi-Channel Wireless Backhauls

Michael Rademacher[1], Senka Hadzic[2(✉)], Philipp Batroff[2], Osianoh Glenn Aliu[2], and Mathias Kretschmer[3]

[1] Hochschule Bonn-Rhein-Sieg, Sankt Augustin, Germany
michael.rademacher@h-brs.de
[2] Fraunhofer FOKUS, Sankt Augustin, Germany
senka.hadzic@fokus-extern.fraunhofer.de,
{philipp.batroff,osianoh.glenn.aliu}@fokus.fraunhofer.de
[3] DeFuTech UG, Hennef, Germany
mathias.kretschmer@defutech.de
http://defutech.com

Abstract. With the growing potential of wireless backhaul technologies for outdoor environments and rising interest in unlicensed bands for broadband delivery, dynamic channel assignment and improved spectrum utilization is re-emerging as a research topic. In this paper we describe a centralized channel assignment optimization for our wireless backhaul architecture WiBACK. In order to efficiently utilize wireless channels in heterogeneous networks, we propose an improvement to the current frequency planning scheme using 802.11 as an example. The contributions in this paper can improve broadband access for emerging areas, often lacking required telecommunication infrastructure.

Keywords: Channel assignment · Frequency planning · Wireless backhaul · Spectrum optimization · Rural areas · Mesh networks

1 Introduction

A backhaul network bridges the gap between the backbone and the access network. Different technologies can be used for the backhaul, such as Ethernet, digital subscriber line (DSL), synchronous/plesiochronous digital hierarchy (SDH/PDH) interfaces or wireless technologies. Today, wireless backhaul networks are used to extend, complement or even replace traditional operator equipment, to relay end-user traffic from access points to the backbone. Wireless Backhauls (WiBACKs) goal is to extend the Internet coverage while keeping

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the investment cost low. Wireless backhaul deployments provide a solution for broadband access especially in rural areas, where the lack of sufficient profitability prevents operators to invest in infrastructure. Another characteristics of rural areas that impose challenges are the lack of energy access, shortage of skilled labor, huge distances and low population density. All these factors contribute to very high OPEX/CAPEX. WiBACK, a wireless backhaul solution developed at Fraunhofer FOKUS makes use of heterogeneous multi-radio nodes, forming point-to-point links in order to extend the broadband coverage. Details on WiBACK will be provided in Sect. 2.1.

In multi-radio networks, smart channel assignments are desirable for several reasons. The most common motivation is to minimize the interference from external networks, but also to improve the capacity when some links are heavily used, and thereby balance the load over different channels. With the growing adoption of outdoor Wireless Local Area Network (WLAN) and its integration as an essential part of future heterogeneous networks, particularly for traffic offload and backhaul for small cells, new challenges on the opportunistic usage of these channels have to be addressed. Furthermore, channel bonding mechanisms in 802.11n/ac for example, enable the use of wider channels but also increase the likelihood of co-channel interference. Channel occupancy in the unlicensed Industrial, Scientific and Medical (ISM) or Unlicensed National Information In-frastructure (U-NII) band is increasing due to the immense opportunities and applications it can be utilized for. With no rigid regulation on accessibility of channels in this spectrum, it has become pertinent to include a dynamic channel assignment scheme for wireless backhaul networks operating in this ISM band. Therefore we intend to extend our current frequency planning scheme in WiBACK.

The remaining of the paper is organized as follows: In Sect. 2 we present state of the art solutions for channel assignment in multi-radio wireless networks, the current channel assignment implementation in WiBACK and the motivation for our new approach. We propose a solution to improve the existing implementation in Sect. 3 and evaluate the proposed method with results in Sect. 4. Finally, Sect. 5 concludes the paper and gives an overview of our intended future work.

2 Related Work

The simplest approach to multi-radio channel assignment is the Common Channel Assignment (CCA) [1], which assigns channel 1 to the first radio interface of each node, channel 2 to the second radio interface of each node, and so on. This approach demands no coordination among nodes and retains network connectivity. However, it also leads to a high degree of interference and only works with omnidirectional antennas. For this reason, the fixed assignment method CCA usually serves as a baseline for performance comparison. Some papers consider the joint channel assignment and routing problem. Rainwala et al. [2] proposes an iterative routing algorithm based on traffic profiles, using only local traffic load information. It is shown that even with just two network interface cards on each node instead of a single radio, it is possible to achieve up to 8 times higher network throughput.

In general, temporary topology alterations should be avoided or at least minimized, since they may lead to suboptimal routing or even network partitioning. In order to guarantee that the network will remain connected after channel assignment, [3] proposes the use of a default channel, over which the data flow is redirected during resource allocation. The channel assignment problem can be formulated from different perspectives, but mostly used tools are graph theory, multi-objective optimization and game theory. The majority of approaches make use of graph theory to model the interference relationship between multi-radio nodes in a wireless mesh network. The edge coloring problem is formulated as follows: nodes are represented as vertices, and the links form the edges of the graph. A pair of nodes has a link between them in the undirected connectivity graph if they are located within each others transmission range. The graph coloring problem consists in finding the k minimum numbers of colors to paint the edges of a graph so that two adjacent edges are assigned different colors. It is a well known NP[1] hard problem [2]. Semidefinite and linear programming solutions have been proposed to reduce the time complexity of the channel assignment problem. A multi-radio conflict graph, an extension to the regular conflict graph model, has been proposed in [3] to model the interference between multi-radio nodes in a mesh network. Instead of links between nodes, links between single radios are represented as graph edges. Problems arise when the number of interfaces on a node exceeds the number of available channels.

Channel assignment can be seen as a multi-objective optimization problem for which several objectives can be defined with various conflicting constraints and requirements. The problem is in general NP-hard and many heuristics have been proposed [2,4], providing suboptimal solutions. An overview of channel assignment approaches using multi-objective optimization is given in [5].

Both cooperative and non-cooperative game theory can be used as a tool to model the channel assignment problem [6]. In [7] a non-cooperative game is formulated where wireless interfaces act as players, and the player's strategy set is represented by channels available to each player. The utility function is defined to minimize co-channel interference from other players. In practice, most evolutionary algorithms based on game theory and artificial intelligence are not widely adopted by industry due to known issues with their stability [8].

Our proposed solution is thus inspired by existing graph coloring schemes which have been shown to be suboptimal. We therefore define and prioritize a set of objectives including constraints based on real deployments and regulatory issues.

2.1 Current WiBACK Approach

WiBACK is a self managing wireless backhaul network, with deployment scenarios ranging from last-mile service provisioning to wide-area coverage in emerging

[1] Non-deterministic Polynomial-time.

areas and developing countries. The WiBACK architecture is technology agnostic, making it able to exploit features of low cost off-the shelf hardware like IEEE 802.11 radios to form long distance point-to-point links among multi-radio nodes. In order to meet the QoS requirements, these links must operate on low-interference channels.

The WiBACK architecture can be positioned between access and backbone networks. Controller nodes and Access Points (AP) form the WiBACK interface to external networks. WiBACK can be used to complement existing operator networks, but may also be deployed as a cost-effective low-energy alternative to conventional backhaul networks. Its technology-independent nature allows WiBACK to integrate any type of radio network technology, provided that an appropriate abstract control interface is available. The network control plane is inspired by IEEE 802.21, but extends it to a media independent service platform.

The channel assignment in WiBACK is currently implemented during the ring-based topology forming and is not a centralized process [9]. After a node joins the network, it scans on all free interfaces and choses a frequency depending on the scan results. This is used as input for radio planning since new nodes will scan the spectrum and join on the free interface on the previously defined frequency [10], and therefore acts only on local knowledge without any option of the controller to interfere in case of link degradation. If there are multiple available interfaces to join, a WiBACK node attempts to assign the least utilized channel with the highest Signal-to-noise ratio (SNR).

2.2 Motivation for a New Approach

Existing frequency planning schemes based on graph coloring aim to minimize interference in multi-radio networks. We want to further ensure a high throughput for long distance point-to-point links in a typical WiBACK deployment is achieved. In case of 802.11 long distance links, the major constraint limiting the range is the SNR needed for higher modulations, leading to an increased throughput. However, the SNR is mainly reduced by the Free-space path loss (FSPL) and the effects of Fresnel zone. Moreover, common WiFi-cards operate in the ISM band which is under regulatory restrictions by different organizations and governments. In certain frequency bands, regulatory restrictions might require a maximum allowed transmission power, so it is of interest to use particular frequencies for long range links in order to maximize the throughput. A frequency assignment algorithm for long distance wireless backhaul networks should care that following objectives are met (in descending order):

1. No local interference
2. Maximize the Modulation and Coding Scheme (MCS) used
3. Maximize the guard interval
4. Minimize the number of frequencies used for transmission.

To the best of the authors knowledge there is no solution addressing all these goals under the premise of long distance wireless backhaul links operating in the ISM or U-NII band.

3 Proposed Solution

The fundamental priority of the algorithm is to ensure that links are void of interference from transmission by multiple interfaces at the same node. Based on these unique assignments, we aim to maximize the MCS used for each link based on its distance for throughput maximization. We have provided a detailed mapping of the MCS and throughput in [11]. Maintaining a sufficient guard interval is required as shown in [12]. In the 5 GHz ISM band, Adjacent Channel Interference (ACI) is a problem resulting in SNR degradation and the medium is incorrectly sensed busy. Therefore we maximize the guard interval during the channel assignment, taking into account possible interferences in the spectrum as well as locally used frequencies on the other interfaces. Additionally, we are trying to reuse frequencies in order to improve spectrum utilization.

3.1 Algorithm Design

The algorithm works on the principle of graph edge coloring, with the assigned frequencies represented by the colors. Figure 1 is a flow chart of the steps and decisions taken in the algorithm. We need a regulatory database [13] to know which frequencies can be utilized with which power, to be able to calculate the maximum possible MCS with a given distance at the links. Since we are using a centralized approach, we start at the controller (see Sect. 2.1) and from there on we iterate over all available nodes. At each node we check whether the edges have already a frequency assigned. If that is the case, we can continue to the next edge.

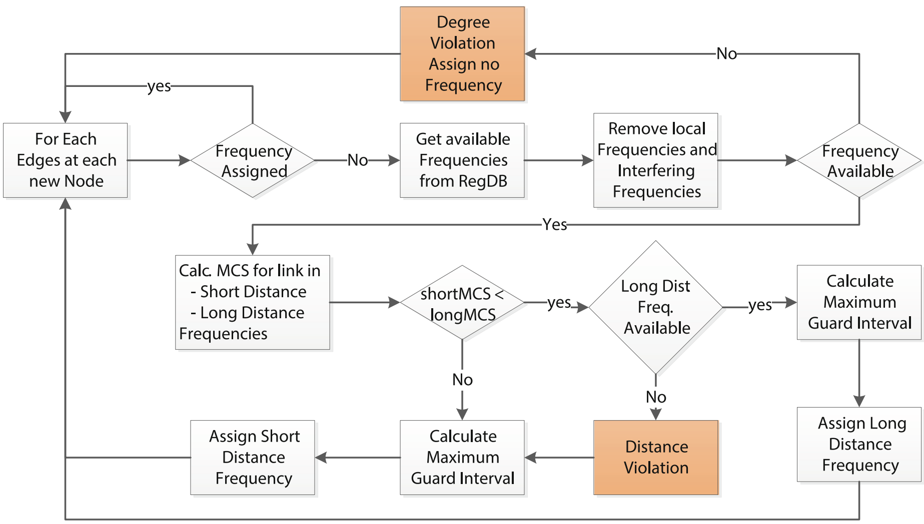

Fig. 1. Flow chart of the algorithm steps

Otherwise we get the available frequencies from the country specific regulatory database and remove the locally interfering frequencies from the other links of the node, as well as the frequencies on the link from possible external interferences.

If no more frequencies are available at this point, we leave the link unassigned and count it as a *Degree Violation* for the validation. If there are frequencies left, we calculate the maximum MCS for the link in the short distance and long distance frequency pool. If the short distance MCS is smaller than the long distance MCS, we use the long distance frequencies, otherwise we apply short frequencies for the link. Then we calculate the maximum guard interval considering the interfering frequencies at the link and the chosen part of the spectrum and assign the resulting frequency. This results in an implicit frequency reuse if the neighbouring nodes have the same amount of interfaces, see Fig. 2.

In case we have to use long distance frequencies but do not have any in the spectrum available, we assign a frequency from the short distance pool with maximum guard interval and denote this edge as a Distance Violation.

4 Verification

We evaluate the performance and reliability of our solution by testing its quality under different simulated network topologies. We create random graphs utilizing the networkx python library [14] based on the concept of a randomized tree which is the common case in existing deployments. It is generated in the simulation by starting at the controller node and adding a random number of edges at the consecutive nodes. For all random processes we use the Linux built-in random device as seed. Every random graph is specified by the number of nodes and the maximum possible degree, and an example is provided in Fig. 2. We assign a random link distance in the range from 1 to 10 km to each link, based on experience in our real deployment scenarios. Interferences are generated randomly on each link as non-available channels for the algorithm, the upper bound being 50 % of the overall available frequencies. Without considering the added advantages of using directional antennas and the vast amount of white spaces in rural areas, we have chosen a worst case scenario to demonstrate the reliability of our solution. To accurately evaluate the maximum possible MCS we calculate the link budget based on the well known concept of FSPL as well as an additional margin of 5 dB[2]. We consider typical hardware currently used for 802.11 based WiBACK nodes. This includes 802.11n WiFi cards (Mikrotik R11e-5HnD), antennas (26 dB gain) and loss occurring from the needed high-frequency cables (1.5 dB) [11]. Because of plans for future build-ups we choose the country of South Africa for our simulation. This especially implies the care and attention of the regulatory restrictions [13] for the 5 GHz ISM band. Two bands with a different maximum possible Equivalent isotropically radiated power (EIRP) are available: 5170–5330 MHz using 20 dBm EIRP and 5490–5710 MHz using 27 dBm EIRP.

[2] The additional margin may be used for compensating a possible Fresnel Zone violation or reflexions.

This leads to a total amount of 21 frequencies assuming a bandwidth of 20 MHz, and 11 for 40 MHz. In our simulation, 1000 random topologies were generated for each combination of input parameters. We evaluate three different output values to measure the quality of our algorithm which are strongly related to the goals mentioned in Sect. 2.2. *Degree Violation* represents a case where the algorithm was unable to assign a free frequency to the current link. *Distance Violation* occurs when the algorithm uses a low power frequency in the case a high power frequency was needed. We quantify this value as percentage of all links. Strongly related to this parameter is the value of *Lost MCS* which describes the overall missed MCS due to *Distance Violations* compared to the maximum possible MCS for a perfect frequency assignment.

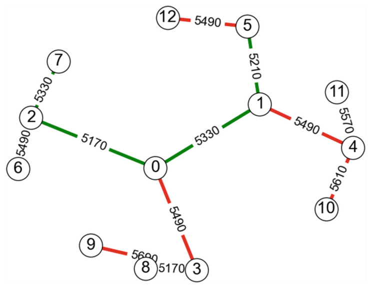

Fig. 2. Example of generated graph. Number of nodes = 13, maximum degree = 3. Low Power links = green, high power links = red (Color figure online).

4.1 Results

In this section we present the results of our algorithm considering two different cases. First, we assume a fixed channel bandwidth of 20 MHz. Afterwards, we conduct the same experiments for 40 MHz channel bandwidth which halves the number of available channels but doubles the throughput as described in [11].

20 MHz Channel Bandwidth. For the case of 20 MHz bandwidth we could not obtain any Degree and Distance Violations for networks sizes of 25, 50 and 100 nodes and a maximum degree ranging from 3 to 9. However, a maximum degree of 9 is unlikely in real deployments. Our algorithm was always able to assign a high power frequency where needed and therefore maximizes the possible MCS on each link.

Figure 3 shows for the same amount of nodes and degrees the number of available and assigned frequencies as well as the average guard interval between local links at nodes. In all cases the algorithm did not exhaust all possible frequencies. However, the needed frequencies increase with the network size as well as with the maximum degree of the network. An important result is that the algorithm assigns frequencies in a way that there is an adequate average guard

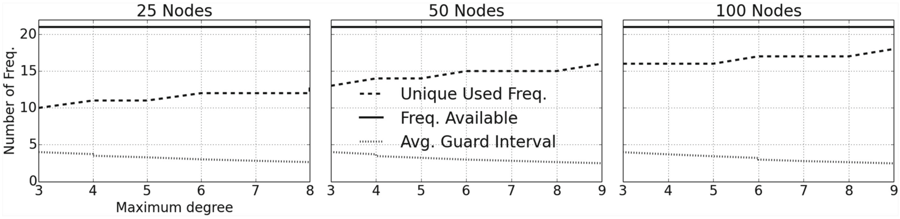

Fig. 3. Results with channel bandwidth 20 MHz. Average link distance: 5,5 km

interval even for high degrees and large networks. The average guard interval ranges from 2.5 (50 MHz) to 4.5 (90 MHz) channels. These values are sufficient to avoid SNR degradation as described in [12].

The average assigned MCS can be observed through the dotted line in Fig. 4. Since the algorithm always assigned the maximum possible MCS for an average link distance of 5.5 km, the average value is constant at 6.4. For lower average link distances or higher available maximum EIRP this value theoretically moves closer to 7.

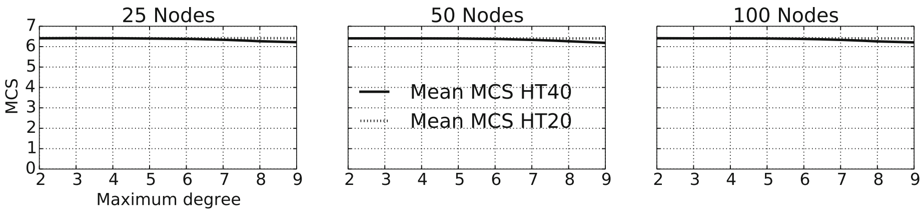

Fig. 4. Average assigned MCS for HT40 and HT20. Average link distance: 5,5 km

40 MHz Channel Bandwidth. A channel bandwidth of 40 MHz is more challenging for the algorithm since a decreased number of channels are available for assignment. This is observable in the results presented in Fig. 5. However, the top row shows again that the algorithm assigned no Degree Violation so there is no local interference for all different network sizes and maximum degrees. This is a surprising result taken into account the high number of simulated interferences and the maximum degrees. However, Distance Violations and the associated Lost MCS occur. This effect is especially evident for a higher degree and for an increased amount of nodes. For the worst-case scenario (network size of 100 nodes, maximum degree of 9) the algorithm assigned at 10 % of the links a short distance frequency where a long distance frequency was preferable. This leads to an overall loss of 15 % of physical throughput in the complete network. However, since 40 MHz channels doubles the possible throughput as described in [11] it is still a preferable choice. The lower row shows a sufficient width of guard interval between one (40 MHz) and two (80 MHz) channels.

The straight line in Fig. 4 shows the average assigned MCS for 40 MHz bandwidth. It can be observed that this value is slightly descending for higher degrees

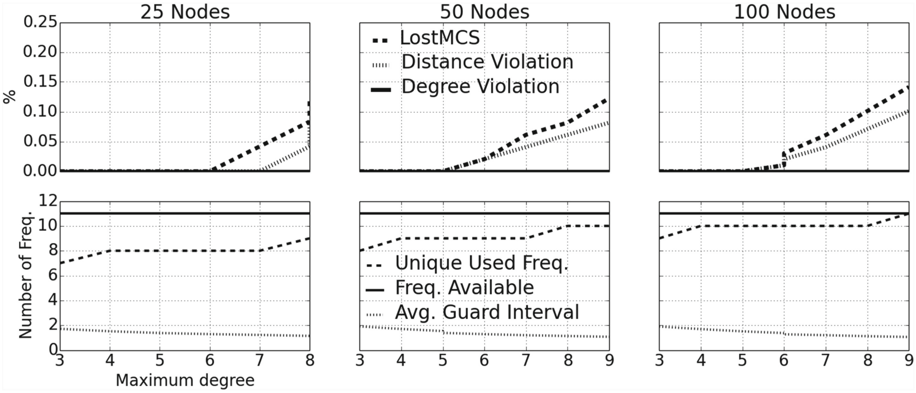

Fig. 5. Results with channel bandwidth 40 MHz. Average link distance: 5,5 km

to a minimum of 6.2. This decrease relates to that Lost MCS in Fig. 5 for higher degrees. However this is still located between the two highest possible MCS, which is a good result for the worst case scenarios used.

5 Conclusion and Future Work

In this paper, we presented a centralized spectrum allocation scheme for wireless backhaul networks using 802.11 as an example. We showed that local interference can be avoided while keeping a guard interval between assigned frequencies. Depending on the number of interfaces at each node and the overall network size, a minimum number of frequencies can be assigned. We showed the difference between an assignment for 20 MHz and 40 MHz channels in the country of South Africa for a large amount of different topologies. We showed that the average assigned MCS is well above 6 for an average link distance of 5.5 km.

As an outcome of this work, several future work items have been identified. While we considered operation on the 20 MHz or 40 MHz channels, a mixed operation may be desirable. Instead of using the MCS for distinguishing between long and short distance links we intend to use the approximated layer 3 throughput as described in [15]. The influence of directional antennas [11] on local interference in combination with geographical location of the nodes may be an interesting approach as well. A centralized spectrum management allows us to incorporate other technologies into our algorithm such as TV-White Spaces (TVWS). Additionally continuous optimization, error handling and Dynamic Frequency XSelection (DFS) restrictions need to be considered.

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