Effects of Link Rate Assignment in IEEE 802.11 Mesh Networks

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Abstract—**The IEEE 802.11 standard supports a variety of modulation and coding schemes (MCSs). In 802.11-based wireless mesh networks (WMNs) it is hence possible to adapt the link rate to the channel conditions. In particular, smaller link rates may be accepted for an increased spatial reuse. In an earlier study, we showed that this effect is suitable for increasing the max-min fair share throughput in a WMN operating with a TDMA channel access scheme. In this work, we investigate if the use of smaller link rates is also suitable for increasing the throughput of a WMN using a contention-based channel access mechanism. For this purpose, we analytically derive a guideline for link rate assignment as protection against hidden nodes and compute the costs and benefits of this mechanism in terms of MAC layer efficiency. A simulation study shows however that in a medium-sized WMN this strategy is less advantageous than assumed and allows to give advices for practical mesh network deployments.**

I. INTRODUCTION

During the last years, wireless mesh networks have become popular for fast, reliable, and cost-effective wireless network deployment as they are self-organizing, self-configuring, and self-healing [1]. Thus, WMNs are no longer only in focus of research, but are increasingly used in private neighborhoods, small companies, or cities for providing Internet access. Although the topology and hardware of those Internet access mesh networks varies strongly, they have one common characteristic: A number of mesh nodes provide Internet access to clients by forwarding traffic from and to a subset of mesh nodes which serve as gateways to the Internet.

Nodes far away from gateways rely on nodes in vicinity of the gateways for forwarding their traffic. Policies for guaranteeing a minimum amount of bandwidth for all nodes are hence a viable way for increasing the network performance and many authors, e.g. [2]–[5], propose mechanisms for guaranteeing fairness in WMNs. Most flow rate allocation schemes guaranteeing fairness (e.g. [2], [4], [5]) assume an optimal channel access scheme which is able to perfectly allocate the specified number of time slots to a node. If the network is however only using the basic contention-based channel access, dedicated flow rate assignment is not possible. A fair radio resource utilization is hence much more difficult, see e.g. [3] for an approximative solution.

As the IEEE 802.11 amendment for mesh networking, IEEE 802.11s [6], is not yet fully accepted, the default contention based IEEE 802.11 distributed coordination function (DCF) [7] is the predominant channel access scheme in unplanned community mesh networks. Such mesh networks run in general no algorithms striving for fairness, but the popularity of mesh networking initiatives like the German "freifunk" community [8] is nevertheless increasing as they enable an ubiquitous Internet access. The optimization possibilities for likewise WMNs are limited, as the topology and routing structure and most often also the channel number and transmission output power are given. This paper examines one possibility for increasing the performance of WMNs under the aforementioned restrictions. We namely examine in how far adaptive modulation and coding (AMC), i.e. a dedicated link rate assignment is advantageous for the network throughput.

The reason why we think AMC to be suitable for WMN optimization is the following: Most commonly, it is assumed that two nodes communicate at the highest possible data rate for maximizing the throughput, e.g. [9], [10]. If, in contrast, an MCS with a smaller data rate is used for link x, this on the one hand clearly decreases the link rate. On the other hand it could allow the use of x at the same time as a potentially interfering link, hence, allow a higher degree of spatial reuse. In an earlier study, we showed that this effect may increase the average max-min fair network throughput in a WMN where the radio resource can be optimally used as e.g. a TDMA channel access is existing [11]. Under a contention based channel access scheme, the resource allocation is not perfect, but the MAC efficiency can also benefit from this effect: RTS and CTS do not guarantee an exclusive channel reservation, as hidden nodes which were not able to decode the CTS could interfere the transmission. We therefore derive a rule for an MCS selection which minimizes the harmful impact of hidden nodes and analyze the costs and benefits of this protection. Additionally, we report on the effects of a more robust MCS choice in a simulation study.

The paper is structured as follows: In Section II contributions which are related to our problem are discussed. Section III introduces the required analytical framework. In Section IV, we explain how AMC can be used for network optimization. Numerical results are presented in Section V. Section VI concludes our work and gives an outlook on future research directions.

II. Related Work

We are interested in the question whether there is an optimal way for assigning link rates in WMNs with a contention-based channel access scheme. In this section we therefor review contributions to characterizing the performance of a WMN and to link rate adaptation. Many studies exist which aim at characterizing the performance of wireless networks in terms of throughput under the assumption of an interference-free channel access. The study of Gupta and Kumar [12], who give upper bounds for wireless networks with random traffic patterns, is the most prominent example of this category. Common to this and other works is that the results can be hardly applied to WMNs where the traffic flows are all either going to or coming from the Internet gateways and where fairness is vital. In a previous study [4], we proposed an extension of the work of Aoun and Boutaba [2] who describe an algorithm for max-min fair capacity calculation in WMNs with one Internet gateway where all links use the same rate. The effective load based algorithm (ELBA) introduced in [4] allows to compute the max-min fair throughput of a WMN with multiple gateways and multiple link rates. The max-min fair throughput computed by ELBA is used in this study and in [11] as a benchmark for the throughput achievable under optimal conditions. In a recent contribution to WMN engineering, Luo et al. [5] used a similar but more easy to compute optimization criterion: They investigated the joint routing, scheduling, rate adaptation, and power control which maximizes the minimal per flow throughput. The authors also show that the impact of design decisions observed under this criterion hold for the proportional fair throughput.

The concept of *effective load*, used by ELBA, was already introduced in [2], but no details on its computation were given. To compute the effective load of a link, we determine which transmissions may be scheduled at the same time by computing cliques in the *contention graph* $\mathcal{G_C}$. The vertices of $\mathcal{G_C}$ are the active links between the mesh nodes. An edge between two vertices exists, if the two corresponding links are *contending*, i.e. may not be used in parallel. The cliques in this graph give now the set of links whereof at most one link can be active. The effective load of a clique is computed as the sum of all flows traversing links of this clique. ELBA achieves a max-min fair rate allocation by iteratively allocating the maximal feasible rate to the flows traversing the bottleneck clique. For a more elaborate description refer to [4], for this work it is just important to keep in mind, that this procedure results in a max-min fair per-flow throughput.

In random access networks, the achievable throughput is not as simple to compute. The interaction of contention mechanisms introduces a random element and does not allow a deterministic channel access. That is why we use the average network throughput obtained by simulation in our work. This methodology has e.g. also been used by Vannier and Lassous [3] who establish an *ns-2* simulation study for proving that their rate allocation protocol is reasonable in multi-hop networks with a contention based channel access.

For the second problem, the link rate adaptation, a large number of practically implemented algorithms exist which dynamically adapt the link rate to the channel conditions. Lacage et al. [9] review existing approaches and propose an own dynamic mechanism which allows to significantly increase the average network throughput. While the focus of most mechanisms is the maximization of the link rate in dependence on the actual channel conditions, it has rarely been analytically studied whether selecting smaller link rates is beneficial for the network throughput. One of the rare contributions in this area is the work of Toumpis and Goldsmith [13] who develop a mathematical framework for studying how the performance of mobile ad-hoc networks can be optimized. The authors found that spatial reuse, i.e. using lower transmission rates and in turn allowing more concurrent transmission is increasing the network throughput. Due to its complexity, the proposed framework is limited to small network instances and does not allow to give qualitative statements for specific network instances. More applicable for mesh networking is the study of Max et al. [14] which analyze the effect of AMC on the capacity of mesh networks. The authors assume an optimal MAC protocol and a given routing structure, and describe how to schedule concurrent transmitters, transmission durations, and rates in order to satisfy the traffic demands. They prove that smaller link data rates allow for an increased number of concurrent transmissions and hence an increased system throughput, a result which is similar to the one we obtained in [11]. Comparable insights are however not known for WMNs with a contention based channel access scheme, we will therefore attack such a study in the following.

III. Analytical Framework

This section introduces the analytical framework we use in the following. The network abstraction is explained in Section III-A. More details on the formal representation of AMC and link rate assignment are given in Section III-B.

A. Network abstractions

We formalize a WMN as $\mathcal{C} = (\mathcal{N}, \mathcal{L})$ where $\mathcal{N}$ denotes the set of mesh nodes and $\mathcal{L}$ the set of links. $(x, y) \in \mathcal{L}$ exists, if nodes $x, y \in \mathcal{N}$ are able to communicate. Each link $(x, y) \in \mathcal{L}$ operates with rate $r_{x,y} = r_m$ which is given by the used MCS m. We assume that all mesh nodes use the same channel. A subset of the mesh nodes are gateway nodes connected to the Internet. All other mesh nodes are used as access points for end-users and hence are the destination of a best effort flow from the Internet which is routed via one dedicated gateway.

The power received at node y when x is transmitting, $R_{x,y}$, can be computed by a simplified path loss model proposed e.g. by Goldsmith [15]:

$$R_{x,y} = TG_{x,y} = TK[\frac{d_0}{d_{x,y}}]^\alpha = T\beta d_{x,y}^{-\alpha}. \tag{1}$$

We assume the node transmission power, T, to be the same for all nodes. $G_{x,y}$ denotes the path gain between x and y which we model as time invariant. It is computed using the

unitless constant K which captures the antenna characteristics and the average channel attenuation, the reference distance d_0 and the path loss exponent α. To simplify the notation, we additionally introduce $\beta = K d_0^\alpha$.

A time independent measure for the channel quality between x and y is the *signal to noise ratio* (SNR)

$$\gamma'_{x,y} = \frac{R_{x,y}}{N}, \tag{2}$$

where N denotes the ambient noise power. y can however only decode x's transmission if the *signal to interference and noise ratio* (SINR), $\gamma_{x,y}$, is large enough. It is computed as

$$\gamma_{x,y} = \frac{R_{x,y}}{N + I_{x,y}} = \frac{R_{x,y}}{N + \sum_{z \in \mathcal{Z}} R_{z,y}}, \tag{3}$$

where the time varying interference, $I_{x,y}$, is computed as the sum of the powers received from the nodes which are transmitting at the same time as x, $z \in \mathcal{Z} \subset \mathcal{N}$. Obviously, the values of both, SINR and interference depend on the time of observation, a more exact notation would thus be $\gamma_{x,y}(t)$ and $I_{x,y}(t)$. For reasons of convenience we however drop the variable t, unless it is necessary. If the interference is zero, i.e. no node is transmitting at the same time as x, then $\gamma_{x,y} = \gamma'_{x,y}$, otherwise $\gamma_{x,y} < \gamma'_{x,y}$.

B. Adaptive Modulation and Coding

A detailed definition of AMC can be found in [15]. Roughly speaking, it is a method for adapting the robustness of a transmission to the channel conditions. A link which is used with a high data rate supports less concurrently transmitting nodes than a link which is used with a lower data rate as this means a more robust modulation and coding scheme.

The IEEE 802.11 standard [7] offers a discrete set of MCS $\mathcal{M}$. Each MCS $m \in \mathcal{M}$ has a unique data rate r_m and a threshold SINR, γ_m^*, which must be exceeded for a successful reception. Node y is able to decode a transmission from x with MCS m, if

$$\gamma_{x,y} \geq \gamma_m^*. \tag{4}$$

An optimal AMC mechanism would allow to use for each transmission the highest data rate which still allows to decode the signal. In analogy to [13], we formalize AMC in this scenario by introducing the function q which maps the link SINR to a link data rate provided by $\mathcal{M}$, i.e.

$$q(\gamma_{x,y}) = \max_{m \in \mathcal{M}} \{r_m : \gamma_m^* \leq \gamma_{x,y}\}. \tag{5}$$

If the link rates shall be statically assigned before a WMN with an unknown traffic pattern becomes operational, a perfect AMC mechanism is not feasible as the SINR is time varying and not predictable in advance. The SNR in contrast, depends on the constant path gain only. Therefore, we use the link SNR for integrating AMC in the network planning process and assign to each link (x,y) the rate which is given by

$$r_{x,y} = q(\gamma'_{x,y}). \tag{6}$$

Using Eq. (6) results in link data rates which are larger or equal to the ones computed by Eq. (5). This is simply due to

the fact that q is monotonically increasing and that the SNR is always larger or equal than the SINR. The downside of this approach is that transmissions on this link may fail in the presence of concurrent transmissions.

For a more *conservative* link rate assignment, i.e. a more robust MCS choice which enables a receiver to successfully decode a transmission despite a certain amount of interference, we use the link SNR together with the *interference buffer* $\Delta\gamma$. The latter can be seen as a safety margin for a certain amount of interference which comes at the price of a decreased link rate. An interference buffer for link (x,y) guaranteeing the transmission success on (x,y) in the presence of any amount of interference would formally be given by

$$\Delta\gamma_{x,y} = \max_t \frac{\gamma'_{x,y}(t)}{\gamma_{x,y}}. \tag{7}$$

A conservative link rate assignment strategy using the interference buffer is formulated by replacing Eq. (5) by

$$q_{IB}(\gamma'_{x,y}, \Delta\gamma_{x,y}) = \max_{m \in \mathcal{M}} \{r_m : \gamma_m^* \leq \frac{\gamma'_{x,y}}{\Delta\gamma_{x,y}}\} \tag{8}$$

would hence allow to transmit successfully in the presence of an arbitrary number of interfering nodes. If a link (x,y) could suffer from a large amount of interference e.g. by one sender close to y, this concept would lead to link rates set to 0. In general, any $\Delta\gamma > 0$ increases the probability of transmission success, but comes at the price of link rate reduction. The next section will therefore explore this trade-off more throroughly and discuss how to find a suitable parametrization for $\Delta\gamma$.

IV. USING AMC FOR NETWORK OPTIMIZATION

In this section, we explain how AMC may be used for optimizing the WMN performance. In Section IV-A we derive a parametrization for the interference buffer which protects a transmission against interference from a given number of interferers. Section IV-B introduces a framework for analyzing the impact of this approach on the network throughput.

A. Parameterizing $\Delta\gamma$ for Collision Protection

The location of the mesh nodes may be modeled as point process $\Phi = \{X_i\}$, where the node locations are given by $\{X_i\}$. In the following, we derive the cumulative distribution function (CDF) of the interference I seen by an arbitrary point of Φ for the case that Φ is a stationary Poisson process with density λ. For this model, two key assumptions hold: (1) The number of points in a bounded Borel set of size A, $\Phi(A)$, follows a Poisson distribution with mean λA, and (2) the number of points in disjoint sets are independent [16].

The kth nearest neighbor of an arbitrary point $p \in \Phi$ is the point of Φ whereof the distance to p, L_k, is larger than the distance between p and $k-1$ other points of Φ. The CDF of L_k is hence given by the probability that the circle around p with radius L_k, $C(p, L_k)$ contains at least k points of Φ:

$$\begin{aligned} F_{L_k}(x) &= P(L_k \leq x) = 1 - P(\Phi(C(p, L_k)) \leq k - 1) \\ &= 1 - \sum_{j=0}^{k-1} \frac{(\lambda \pi x^2)^j e^{-\lambda \pi x^2}}{j!}. \end{aligned} \tag{9}$$

We consider mesh networks where RTS/CTS is used, and assume that the distributed channel access coordination is working as intended, i.e. that no node having received the RTS of x or the CTS of y is interfering the transmission between x and y. For compatibility and robustness reasons, those command messages are encoded by the most robust available MCS m_C [7]. This allows to derive a lower bound for the distance to any interferer z, $d_{y,z}$, if a too small SINR is the only reason for not receiving the CTS:

$$\gamma_{y,z} < \gamma^*_{m_C} \quad \Leftrightarrow \quad \frac{T\beta d_{y,z}^{-\alpha}}{N + I_{y,z}} < \gamma^*_{m_C}$$

$$\Leftrightarrow \quad d_{y,z} > \sqrt[\alpha]{\frac{T\beta}{\gamma^*_{m_C}(N + I_{y,z})}}. \quad (10)$$

Command messages are short. The probability that no interference is present if the CTS is sent, is thus high and we therefore use $I_{y,z} = 0$ in Eq. (10). Under the assumption of symmetric path gains, this leads to a lower bound for the distance L^* to any interferer as the distance to any node which was not able to decode the CTS

$$\sqrt[\alpha]{\frac{T\beta}{\gamma^*_{m_C} N}} =: L_I. \quad (11)$$

Taking this into account, the CDF of the distance L_k^* to the kth nearest interferer is given by the probability that there are at least k nodes of Φ in the ring where all points of the plane lie in which are closer to a point p than L_k^*, but farther away than L_I

$$\begin{aligned} F_{L_k^*}(x) &= P(L_k^* \leq x) \quad (12) \\ &= 1 - P(\Phi(C(p,x) \setminus C(p, L_I)) \leq k - 1) \\ &= \begin{cases} 0 & \text{if } x \leq L_I \\ 1 - \sum_{j=0}^{k-1} \frac{(\lambda\pi(x^2 - L_I^2))^j e^{-\lambda\pi(x^2 - L_I^2)}}{j!} & \text{otherwise}. \end{cases} \end{aligned}$$

Without a detailed knowledge of the traffic pattern, it is unknown which nodes actually disturb a transmission. We therefore use the worst case assumption that the Z nodes of Φ closest to the destination of a transmission are interfering to obtain an upper bound for the interference viewed by any destination of a transmissions as

$$I = T\beta \sum_{j=1}^{Z} L_j^{*-\alpha}. \quad (13)$$

This assumption allows to compute the CDF of I as

$$F_I^Z(x) = P(I \leq x) = P(\sum_{j=1}^{Z} L_j^{*-\alpha} \leq \frac{x}{T\beta}). \quad (14)$$

Having derived a CDF for I, we now focus on finding a network wide value of $\Delta\gamma$ which guarantees the collision free operation of the network if it is used for assigning link rates according to Eq. (8). With Eq. (3) and (2) we obtain a lower bound for $\Delta\gamma$ as

$$\Delta\gamma \geq \frac{N + I}{N} \Leftrightarrow \Delta\gamma \geq 1 + \frac{I}{N}, \quad (15)$$

where the random variable I represents the interference disturbing the transmission between any nodes $x, y \in \Phi$.

Combining Eq. (15) and Eq. (14), allows to compute the probability $P_{\Delta\gamma}^Z(x)$ which gives the probability of a collision free operation in the presence of Z interferers if $\Delta\gamma(Z) = x$:

$$\begin{aligned} P_{\Delta\gamma}^Z(x) &= P(\Delta\gamma(Z) = x \geq 1 + \frac{I}{N}) \\ &= P(I \leq N(x - 1)) = F_I^Z(N(x-1)). \quad (16) \end{aligned}$$

The geometric interpretation of Eq. (16) for the link (x, y) and $Z = 1$ is the following: Due to RTS/CTS, the distance between any interferer and y has to be greater than L_I. For a successful decoding of the transmission, there must however exist a circle with a radius $L_S \geq L_I$ around y which is free of interferers. The closer the link SNR is to the SINR threshold of the selected MCS, the larger must this circle be. Any positive value for the interference buffer decreases this distance. From Eq. (15) and (13), a lower bound for L_S can be derived as follows:

$$\Delta\gamma(1) \geq 1 + \frac{T\beta L_1^{*-\alpha}}{N} \Leftrightarrow L_1^* \geq \sqrt[\alpha]{\frac{T\beta}{N(\Delta\gamma(1) - 1)}} =: L_S. \quad (17)$$

With one interfering node the transmission will be successfully terminated, if this node is not in the ring with outer radius L_S and inner radius L_I. As soon as $\Delta\gamma(1)$ is large enough to guarantee $L_S \leq L_I$, the probability of collision free operation will be 1. Formally, the probability for a collision free operation may be derived from Eq. (14) and (16):

$$\begin{aligned} P_{\Delta\gamma}^1(x) &= F_I(N(x-1)) = 1 - F_{L_1^*}(L_S) \\ &= \begin{cases} 1 & \text{if } L_S \leq L_I \\ e^{\lambda\pi(L_S^2 - L_I^2)} & \text{otherwise}. \end{cases} \quad (18) \end{aligned}$$

The condition to guarantee collision avoidance in the presence of one interferer, i.e. $P_{\Delta\gamma}^1(x) = 1$ and therefore an interference buffer for collision free link rate assignment develops to

$$\sqrt[\alpha]{\frac{T\beta}{N(\Delta\gamma(1) - 1)}} \leq L_I \Leftrightarrow \Delta\gamma(1) \geq \frac{L_I^{-\alpha}T\beta}{N} + 1 = \gamma^*_{m_C} + 1. \quad (19)$$

Due to the non-linear interdependency of interferer distance and interference strength, a closed form analytical expression and a geometrical interpretation for $P_{\Delta\gamma}^Z(x)$ with $Z > 1$ is more complex to derive, but also possible. Likewise, a collision avoidance value $\Delta\gamma(Z)$ for $Z > 1$ could be computed. In this work we use however only the formula for $Z = 1$ for demonstrating the potential of the interference buffer.

B. Costs and Benefits of $\Delta\gamma$

In this section, we asses the advantages and disadvantage of using the interference buffer for link rate assignment in terms of achievable link throughput more closely. For this purpose, we derive a simple model of the standardized 802.11 DCF mechanism for data packets which are large enough to require an RTS/CTS exchange. All variables which we do not

explicitly introduce in the following are constants defined in the standard [7]. A rough model of the time $t_{tx}(p,m)$ required for transmitting a packet with p payload bits and MCS m in the optimal case, i.e. if no other node is accessing the channel is given by:

$$t_{tx}(p,m) = \text{DIFS} + t_{bo} + \delta(p_{\text{RTS}}, m_C) + \text{SIFS}$$
$$+\delta(p_{\text{CTS}}, m_C) + \text{SIFS} + \delta(p,m) + \text{SIFS} + \delta(p_{\text{ACK}}, m). \quad (20)$$

The random backoff time, t_{bo}, is uniformly distributed between 0 and CW multiples of aSlotTime, where CW is varying between aCWmin and aCWmax, depending on the backoff stage. The time required for sending p payload bits over the channel, $\delta(p,m)$, depends on the used MCS m and on the physical layer. For the case of OFDM in the 5 GHz band, it can be computed as [7]

$$\delta(p,m) = T_{PREAMBLE} + T_{SIGNAL}$$
$$+T_{SYM} \cdot \lceil (16 + 8 \cdot p + 6)/N_{DBPS}(m) \rceil. \quad (21)$$

The number of coded bits per OFDM symbol, $N_{DBPS}(m)$ is increasing with the data rate r_m. RTS and CTS messages are sent using the most robust MCS, m_C which is supported by all stations, where the ACK is sent using the same modulation scheme used for the data packet.

Obviously, Eq. (20) is only valid, if the transmitting node does not encounter any problems. The occurrence of problems may affect the packet transmission in various ways and increases of course the transmission time. Firstly, a packet could be detected during backoff. In this case, which we denote by *db* for *disturbed backoff*, the backoff counter will be frozen and continues to decrement as soon as the channel is sensed idle again for a time DIFS. Secondly, the RTS/CTS exchange could fail, i.e. a *signaling failure*, *sf*, could occur. A sending node detects a failed RTS/CTS exchange if no CTS was received during the CTSTimeout interval after the RTS was sent. The last case which could happen is a *data failure*, *df*, i.e. the node does not receive an acknowledgment during the ACKTimeout interval after having sent the data packet. In this case, the entire RTS/CTS exchange procedure has to be repeated. Both *sf* and *df* can occur a predefined number of times during a successful data exchange [7].

The average network throughput using the correct probabilities for each event could be derived as proposed by Bianchi [17]. As these formulas are only valid for saturated throughput and are very complex, we just concentrate on the effect of the type of failure which can be prevented using the interference buffer, namely the failure of a data packet. RTS and CTS are always sent with the same MCS. The *df* failure is hence the only failure which can be avoided by a more robust MCS choice. If l data failures occur during the transmission of p payload bits, the required time increases to [7]

$$t_{tx}^{df}(p,m,l) = \sum_{i=1}^{l+1} t_{bo}^i + l \cdot \left[\text{DIFS} + \delta(p_{\text{RTS}}, m_C) + \text{SIFS} \right.$$
$$+ \delta(p_{\text{CTS}}, m) + \text{SIFS} + \delta(p,m) + \text{ACKTimeout} \right]$$
$$+ \text{DIFS} + \delta(p_{\text{RTS}}, m_C) + \text{SIFS} + \delta(p_{\text{CTS}}, m_C)$$
$$+ \text{SIFS} + \delta(p,m) + \text{SIFS} + \delta(p_{\text{ACK}}, m). \quad (22)$$

For its computation we have to add the time required for $l+1$ backoff phases with increasing contention windows, t_{bo}^i, the time for l failed data exchanges and for one successful one.

In order to derive a model for the effects of $\Delta\gamma$ on the average network throughput, we assume that data failures are the only events which could occur. This is insofar justified as the interference buffer has no positive influence on the occurrence of the other events and we are only interested in studying the impact of MCS choice. For the case, where all data packets have the same amount of payload, P, and with a probability of ρ, exactly $l = 1$ data failure occurs during a transmission, the throughput $\tau(m)$ under MCS m can be computed as

$$\tau(m) = \frac{P}{(1-\rho)t_{tx}(P,m) + \rho t_{tx}^{db}(P,m,1)}. \quad (23)$$

Clearly, the model is very simplistic as it does not include the effect of a varying number of data failures. Moreover is ρ depending on the used MCS and on the network environment. This formula nevertheless allows to illustrates the double-edged influence of a $\Delta\gamma > 1$ which both increases the transmission times and reduces the *df* failure probability.

V. NUMERICAL RESULTS

For illustrating the potential of the previously introduced framework we give some numerical examples. We focus at 802.11 WMNs operating with an OFDM PHY in the 5 GHz band. In this case, 8 different MCS enabling data rates between 6 and 54 Mbps are available [7]. The SINR requirements γ_m^* and the maximal feasible transmission distances which allow to meet a frame error rate of 1% when an IP packet with 1500 Byte payload is transmitted over an AWGN channel of bandwidth $W = 20$ MHz are obtained by link level simulations. The channel model introduced in Eq. (1) is parametrized for modeling a typical mesh network: The ambient noise N is set to the product of the thermal noise spectral density, $N_0 = -174$ dBm/Hz, a typical receiver noise figure of 7.5 dB and W, i.e. $N = -93.5$ dBm. In decibel scale for a reference distance of $d_0 = 10$ m and a path loss exponent $\alpha = 4$, the power received by j is

$$R_{i,j} = T + G_{i,j} = T - 140.046 - 40 \cdot \log_{10}(d_{i,j}), \quad (24)$$

where $d_{i,j}$ is the distance of nodes i and j in kilometer and all nodes use the same transmission power $T = 100$ mW.

In the remainder of this section, we show first numerical examples for the theoretical benefits of more robust link rate assignment in Section V-A, before we report on the results of a simulation study in Section V-B.

A. Effects of AMC on Collision Probability and Link Throughput

We use the framework presented in Section IV-A to derive the interdependency between the probability of a collision-free operation and a specific value of $\Delta\gamma$, $P_{\Delta\gamma}^Z(x)$. In Fig. (1) we show this probability for the case of $Z = 1$ interferer and network densities increasing from one node per 50 m² to one node per m². The probability for collision free operation is the
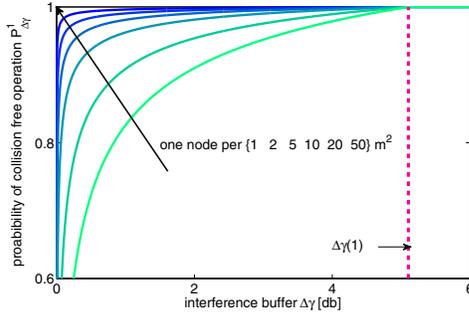
Figure 1. Probability of collision free operation

Figure 2. Average throughput with 1.5 kB payload

highest for a small node density, and also increases with increasing values of $\Delta\gamma$. We additionally show $\Delta\gamma(1) = 5.1$ dB which guarantees a collision-free operation for the case of $Z = 1$ interferer derived from Eq. (19). Due to border effects, the number of neighbors in a real mesh network and in an ideal Poisson field with the same density is always smaller. The probabilities shown in Fig. (1) are thus a mere guideline and have to be adapted to an actual deployment for quantitative statements. The qualitative statement, i.e. that the interference buffer becomes more important for collision avoidance with an increasing number of nodes or higher node activity is however directly applicable.

In Fig. (2) we analyze the effect of data failures on the link throughput. For this purpose, the feasible link length for each of the 7 available MCS if no interference buffer is used, is computed via Eq. (24). The throughputs for the case that with probability $0 \leq \rho \leq 0.2$ each data packet encounters one data failure are calculated using Eq. (23) and shown with dashed lines. The solid line depicts the resulting throughputs if link rates are assigned using $\Delta\gamma(1) = 5.1$ dB. As we assume that all failures which could occur are data failures caused by one interfering node, the collision probability is hence 0.

This representation allows to see that the quantitative negative impact of failures on the throughput of short, i.e. high data rate links is larger than on longer, low data rate links. This is due to the fact that the RTS/CTS exchange, which is done with the slowest link rate, has to be repeated. The time penalty of a failure in comparison to a data transmission is hence larger for fast links than for slow ones. Consequently, using $\Delta\gamma(1)$ for link rate assignment is most beneficial for high data rate links. For links with a medium link rate, this pays only if the collision probability and thereby the loss of transmission efficiency is high. In the case of links with a length over 130 m, the use of $\Delta\gamma(1)$ for link rate assignment would even result in a throughput of 0, as those links could simply not be used anymore. The analysis presented in Fig. (2) is valid for one hop only. The next section therefore studies $\Delta\gamma$'s effects in a multi-hop environment.

B. Effects of AMC in a RTS/CTS based WMN Deployment

In order to evaluate the effects of the interference buffer in a realistic WMN deployment, we use 200 network samples consisting of 3 gateways and 15 mesh access points each. All numerical values we show in the following are obtained as averages over the 200 different samples and are depicted with the corresponding 95% confidence intervals. The nodes are randomly placed in a square area of 400×400 m with a minimum distance of 100 m between the gateways and 20 between the non-gateway mesh nodes. We choose this methodology to represent a typical unplanned mesh network deployments for two reasons: It firstly allows to specify a minimum distance between the mesh nodes, which is a realistic constraint and secondly increases the comparability of results as the number of nodes per topology is fixed.
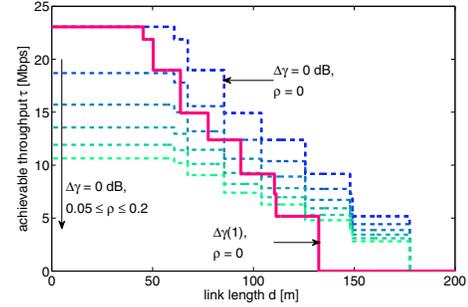
Clearly, the routing topology has a significant impact on the WMN throughput. A comparative study of specific routing protocols is not the goal of this work. We are only interested to what degree the effects of different link rate assignment policies are sensitive to the routing paradigm. For this purpose, we consider three different routing approaches which were already used in [11]. As an abstraction for an ad-hoc routing protocol, we use *Minimum-hop routing (MH)*, where each node forwards its data to the neighboring node which is the closest to a gateway. A more sophisticated mesh routing protocol is modeled by *Maximum-capacity routing (MC)* which establishes paths rooted in the gateways by iteratively connecting the neighbor which is reachable with the highest link rate. For comparison purposes, a chaotic topology is abstracted by *Random routing (R)* which establishes routing trees rooted in the gateways, by iteratively connecting each node to a randomly chosen already connected neighbor.

For each topology, we use $\Delta\gamma = \{0, 2, \ldots, 10\}$ dB for link rate assignment. As illustrated in Fig. (2), long links which exist in topologies with $\Delta\gamma = 0$ dB, might be assigned a zero link rate for $\Delta\gamma > 0$ dB as their SNR is smaller than the smallest SINR threshold plus the interference buffer. In this case, the routing had to be recomputed for each link rate assignment. In [11] we found that this reorganization of the topology is responsible for a significant throughput increase. In order to study the undiluted effect of $\Delta\gamma$, we do not change the routing topology. For this purpose, long links which are already using the slowest rate for $\Delta\gamma = 0$ dB are kept operating at this rate for all values of $\Delta\gamma$.

We evaluate the performance of the resulting 200×6
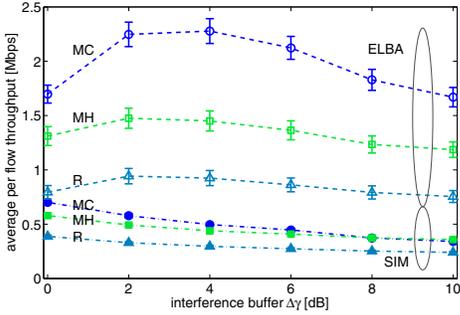
Figure 3.   Max-min fair share vs. simulated average per flow throughput

Figure 4.   Impact of AMC on the topology

WMN deployments under each of the 3 routing paradigms. For this purpose, we calculate the average max-min fair per flow throughput with the algorithm ELBA introduced in Section II and compare it to the output of a simulation. Evaluating the influence of $\Delta\gamma$ in a simulation study is no easy task, as this requires to assign link rates not on a per interface but on a per link base. One wireless interface has thus to use different MCS. In *ns-2* this is e.g. not possible without major modifications of the source code. We therefore implemented our own mesh network simulator in Java. The signal propagation is modeled according to Eq. (24) and used to compute the received signal strength and the amount of cumulative interference. The MAC layer is realized by implementing the 802.11-2007 stack, all necessary constants are set for the OFDM PHY given in [7]. As upper layer protocols, IP and UDP are used. At randomly distributed times within the first simulation second, each of the non-gateway nodes starts a CBR flow from the Internet representing its customer demands. We use a time resolution of 5 μs and can hence simulate only the first 10 seconds of the network life in order to get results for the 3600 considered network configurations in a reasonable amount of time. The initial transient period is completed after at most one second. Results gathered before this time are discarded.

In Fig. (3) the computed average max-min fair share (labeled "ELBA") and simulated network throughputs (labeled "SIM") are shown in dependence of the $\Delta\gamma$ value used for link rate assignment. Results for each of the used routing protocols are labeled accordingly. This representation illustrates several aspects: Firstly, the less efficient resource utilization in a random access network compared to a perfect channel access schedule enabling a fair resource utilization is depicted by the significant difference between the max-min fair throughput and the simulated one. Observe however that the relative differences between the routing protocols are similar under both evaluation techniques. Next, the representation of the max-min fair share throughputs shows the effect we already reported in [11]: For each network configuration, there is a value of $\Delta\gamma > 0$ dB which is able to maximize the network throughput, as the relation between link rates and spatial reuse is optimized. For the case of networks with MC routing, this value is e.g. somewhere between 2 and 4 dB. Observe
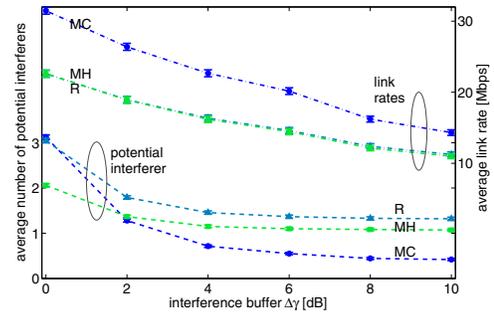
however also, that the throughput increase is stronger for the MC protocol. This is due to the fact that this paradigm prefers links with the highest data rate for which more robust link rate assignment is the most advantageous (cf. Fig. (2)).

Surprisingly, no positive effect of the interference buffer is observable for the simulated network throughput. The average network throughput is instead decreasing and the decrease is moreover strongest for the MC protocol. The reason for this is the effect of $\Delta\gamma$ on the network topology which we illustrate in Fig. (4). We use the y-axis on the left for representing the average number of potential interferers per node. Under this term we understand all mesh nodes which are active, i.e. have data packets to send and which could interfere the transmission to the node. On the right, we show the average data rate of the links which are used in the routing topologies. This representation allows to see that in dependence of the routing protocol, the number of hidden nodes is reduced by over 50% for $\Delta\gamma = 10$ dB. As in turn the link rate is also decreased by roughly 50% it is evident that for large values of $\Delta\gamma$, the link rate reduction can not be compensated any more by the increased channel access time.

Using the average link rates and number of interferers shown in Fig. (4) for a quick calculation and neglecting MAC layer overhead yields that for $\Delta\gamma = 0$ dB and the MC routing protocol, the nodes have on average an available link capacity of $32/(3 + 1) = 7$ Mbps in comparison to $26/(2 + 1) = 8.7$ Mbps when $\Delta\gamma = 2$ dB is used. This result does however contrast the results from Fig. (3), where a decreased average throughput is shown. The reason for this phenomenon is illustrated in Fig. (5). We depict the number of packets which suffered data and signaling failures in relation to the number of transmitted packets. This shows again a double edged influence of $\Delta\gamma$. Observe that the percentage of signaling failures is both larger than the number of data failures and is additionally increasing with $\Delta\gamma$. The latter phenomenon is due to the fact that data packets are longer on the channel, the probability of a concurrent transmission of a signaling and a data packet is hence increasing. Fig. (5) shows however also that the number of data failures is in fact decreasing with $\Delta\gamma$ which is again to a higher degree the case for the MC protocol than for the other ones. This effect can however not compensate the reductions of throughput which
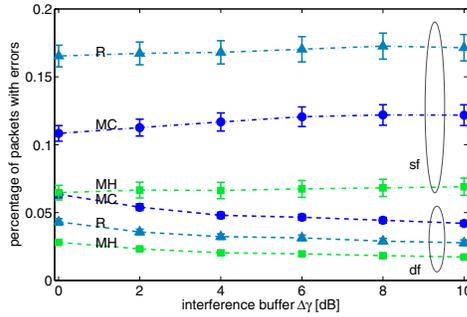
Figure 5.   Impact of AMC on the failure rates

are due to the reduced link rates and the increased number of signaling failures. The total throughput is hence increasing.

All in all, we observed a negative effect of $\Delta\gamma$ on the average throughput in the investigated scenarios, as the amount of decreased collision probability simply does not compensate for the link rate reductions. Moreover can the percentage of data failures never decrease to zero, as we keep the long links operating at lowest data rate. The potential of conservative link rate assignment is thus larger in denser and larger topologies where the routing structure is adapted to the link rate assignment, i.e. where only links with a safety margin of $\Delta\gamma$ between the link SNR and the MCS SINR threshold exists. Networks where the same MCS is used for data transmission and RTS/CTS would also profit more from this method than the configurations we considered. In medium sized WMNs where fairness can not be guaranteed it is hence advisable to assign link rates using $\Delta\gamma = 0$ dB.

VI.   CONCLUSION AND OUTLOOK

In this paper the potentials of link rate assignment for increasing the performance of 802.11-based wireless mesh networks is investigated. A formal framework allows to describe the impact of more conservative than necessary link rate assignment on per link and average network throughput. An analytically derived parametrization for the interference buffer $\Delta\gamma$ enables a collision minimizing link rate assignment for RTS/CTS-based WMNs. The theoretical benefits of this method in terms of increased link throughput are confirmed by an increasing max-min fair share average network throughput if link rates are assigned slightly more conservative than necessary. A simulation study of a WMN with a contention based channel access scheme without fairness guarantees reveals however a throughput decrease. The reason for this is that the type of failures which can be avoided using a more robust MCS have only a small share of the overall failure rate and their reduction does not pay in terms of throughput increase.

All in all, our study proves a double edged impact of more robust link rate assignment for 802.11-based mesh networks. While it is advantageous in networks where fairness can be guaranteed by means of a deterministic channel access, it allows only a marginal failure reduction in networks with a random channel access scheme. Our experiments reveal that

one value of $\Delta\gamma$ does not fit all links in the network. We therefore plan to extend our framework in order to allow heterogeneous protection thresholds. Additionally, we will derive throughput maximizing protection thresholds taking into account traffic characteristics and network configurations.

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