The Impact of Link Adaptation in Narrowband Frequency-selective Wireless Ad-hoc Networks - Part II: The Network Perspective

Sebastian Helmle*†, Mathias Dehm*†, Michael Kuhn†, Dominik Lieckfeldt*, Dirk Pesch‡

*Rohde & Schwarz GmbH & Co. KG, Stuttgart, Germany
†University of Applied Sciences Darmstadt, Darmstadt, Germany
‡Nimbus Centre, Cork Institute of Technology, Cork, Ireland

***Abstract*—This paper in conjunction with its Part I investigates the impact of relaying and adaptive modulation and coding (AMC) on data throughput in narrowband multi-hop wireless ad-hoc networks. In particular, this part focuses on the performance evaluation of scenarios, namely (i) single-hop transmission, (ii) relaying only, (iii) and relaying combined with AMC in a network with time division multiple access and constant/variable bit rate (CBR/VBR) traffic. The results achieved by computer simulations provide insights into the impact on end-to-end net throughput and packet error rate (PER) performance in a wireless ad-hoc network using multiple hops. For our investigation a physical layer for narrowband long range application is considered, which is subject of Part I of this paper. Subsequently, we depict a simulation environment, which contains the detailed physical layer taking into account the Digital Audio Broadcast (DAB) channel model from Part I.**

I. Introduction

In recent years, wireless networks like mobile ad-hoc networks (MANETs), wireless mesh networks (WMN), and wireless sensor networks (WSN) have attracted much interest within the research community. Since they operate without any fixed infrastructure, i.e. ad-hoc, in a completely self-organizing way, the utilization of these types of wireless networks will become more and more interesting for authorities and organizations with security tasks within the next years. Many technologies have been introduced and investigated in the context of cellular networks like GSM, UMTS, and LTE, respectively. However, wireless ad-hoc networks are substantially different from cellular networks regarding their mechanisms for (time) synchronization, link scheduling, Quality of Service (QoS), routing, link adaption, optimized channel access schemes, and relaying schemes. Additionally, the requirements on secure communication also have to be considered, which differ from their commercial counterparts [1], especially in constraints of security restrictions, high coverage (which also leads to limitations in the maximum achievable data rate), robustness against interference and interception, and power consumption. However, future wireless ad-hoc networks should provide services, i.e. constant bitrate (CBR) and variable bitrate (VBR), as already known from cellular networks leading to increasing requirements on the maximum achievable data rate. Furthermore, ad-hoc networks will often be situated in areas with sparse or without any infrastructure like disaster recovery scenarios, where the communication link distance might be even longer than in common (e.g. cellular) environments. Hence, from our perspective, the increase of both, data rate and transmission range could be denoted as the major challenges in future (narrowband) wireless ad-hoc networks.

In this paper, we investigate mechanisms to improve the transmission performance in terms of coverage and data rate with respect to these requirements. For this purpose, we compare (a) single-hop transmission, (b) relaying with fixed transmission parameters (hereinafter referred to as 'relaying only'), and (c) forwarding by means of adaptive modulation and coding (AMC) using previously defined modulation and coding schemes (MCS) from a system level perspective. We evaluate the net throughput as well as the packet error performance with respect to the node density both, for AWGN and DAB channel conditions. In conclusions, our results show the possible amount of data one can transmit in given communication scenarios.

The remainder of the paper is organized as follows: Section II provides the motivation of our investigations based on earlier works. The reference model for our investigations is described in Section III. In Section IV, we depict the simulation environment in general and some details regarding tools and frameworks used. Section V provides information on the parameterization of the computer simulations as well as the results of our investigations. Finally, Section VI concludes our investigations and gives an outlook on our future work.

II. Related Work

As shown in [2], AMC can be used to mitigate the effects of multipath fading in dual-hop networks. AMC in combination with multi-hop networking achieves a good trade-off between throughput and coverage. The authors provide analytical performance results for dual-hop links, i.e. source, destination and relay. Cho et al. investigate in [3] multi-hop networks for multicast broadcast services in mobile WiMAX systems. They adopt an AMC scheme to select an appropriate modulation and coding scheme (MCS) between base station and relay station such that the throughput is optimized. The authors present results from computer simulations showing that the combination of AMC in multi-hop networks with

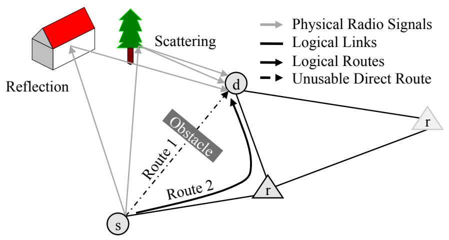


Fig. 1. Adaptive modulation and coding (AMC) using different routes.

infrastructure, i.e. with base stations, can yield improved performance.

In [2], the authors focus on the impact of buffering packets in a dual-hop wireless network employing AMC. They propose two different MCS selection mechanisms: (a) SNR-based AMC and (b) buffer-aware AMC. The authors present analytical results for dual-hop networks only, which show that AMC with buffer-awareness is able to achieve a lower packet loss rate compared to approaches, which leave the buffer level unconsidered.

Relaying schemes are essential in multi-hop (wireless) networks. The most prominent protocols are decode-and-forward (DF) and amplify-and-forward (AF) [4], while DF allows more flexible and adaptive handling of relaying [2]. The survey of recent publications show, that AMC in multi-hop MANETs is still an open research topic. Therefore, this paper contributes results from performance evaluation of AMC using computer simulations based on detailed system and channel models, which are explained in the following.

III. Reference Model

The reference model used for our investigations is shown in Figure 1 and consists of N nodes. There are three types of nodes: the source node (s), which transmits data packets and has fixed coordinates on the simulation area, the destination node (d), which receives data packets and has also fixed coordinates on the simulation area, and the relay node (r), which relays a data packet on its way from the source to the destination node. The source node provides two different types of traffic: (a) constant bitrate (CBR) or real-time traffic such as voice or video data and (b) variable bitrate (VBR) traffic, which should be transmitted to the sink node.

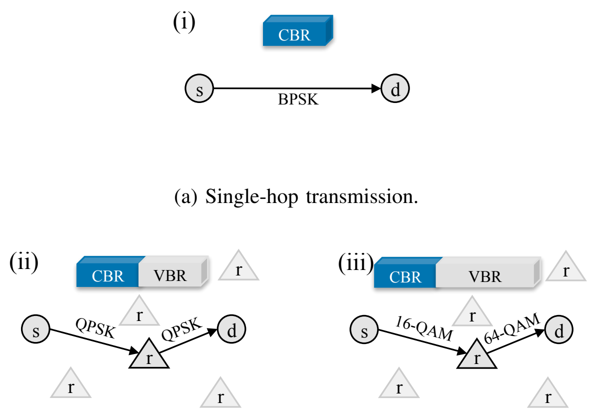
Our reference model utilizes time division multiple access (TDMA) for channel access. The maximum range between source and sink node $d_{99\%,\mathrm{BPSK1/2}}$ is defined to be able to establish a connection in 99% of cases employing the most robust MCS, i.e. BPSK with code rate 1/2. Based on the reference model, the following transmission patterns are considered, which assume different connectivity between source and destination node:

(i) The source node is able to communicate directly with the destination node with high probability (single-hop) using the most robust MCS, i.e. at the lowest data rate. There are no relay nodes.

(ii) The source node uses relay nodes to transmit information to the destination using a fixed MCS without considering current channel conditions.

(iii) The source node transmits the information to the destination node via relay nodes employing an AMC algorithm to adjust transmission parameters according to current channel conditions.

Each of these three transmission patterns (cf. Figure 2) are designed such that minimum requirements for CBR are met in case of single-hop transmission. The VBR traffic is transported via piggybacking whenever link conditions are adequate to transport additional data. In our system, VBR traffic will be



(a) Single-hop transmission.

(b) Relaying only (no AMC).

(c) Relaying combined with AMC.

Fig. 2. Transmission patterns utilized in the reference model. (s) sorce node, (r) relay node, (d) destination node.

transmitted only in transmission patterns (ii) and (iii). The node density D, which is given by

$$D = \frac{N}{A}, \tag{1}$$

where A is the size of the simulation area and N is the number of nodes deployed to the simulation area, significantly affects the total transmission range as well as the throughput on each link and therefore on the entire transmission route. The average node degree $\overline{d}$ used for graph-theoretical analysis can be approximated by

$$\overline{d} = \frac{N}{A}\pi r^2, \tag{2}$$

where r describes the transmission range of each node.

IV. Derivation and Description of the Simulation Environment

The performance parameters are investigated with respect to the transmission patterns described in Section III using computer simulations. In the following, the system model will be clarified including all the underlying assumptions and simplifications.

Takai et al. show in [5], that a detailed and also realistic model of the physical layer is important for the performance evaluation of higher layers. Accordingly, we decided to divide the simulation environment into two separate parts: (a) simulation of the OSI layers two and above and (b) detailed simulation of the physical layer (cf. Figure 3).

The simulation results of the physical layer will be provided to an OMNeT++ [6], [7] simulation framework via lookup tables, in which selected parts of the physical layer and the upper layers are simulated. To implement more realistic physical layer models as well as the different protocols and models used on the layers two and above (hereinafter referred to as the 'upper layers'), additionally the MiXiM [8], [9] framework is incorporated. This open framework provides initial implementations for mobile nodes, physical models, node mobility, and the upper layers.

A. *Network Simulations Including the Upper Layers*

The simulation environment consists of a configurable number of nodes N, which can be distributed either randomly or with fixed coordinates over the simulation area. For the random positioning the uniform distribution is utilized.

As shown in Figure 3, the application layer, which is included in each node, but only utilized within the source and the sink node, is implemented as a particular form of a greedy source [10], which generates traffic continuously at the maximum achievable data rate. The network layer employs

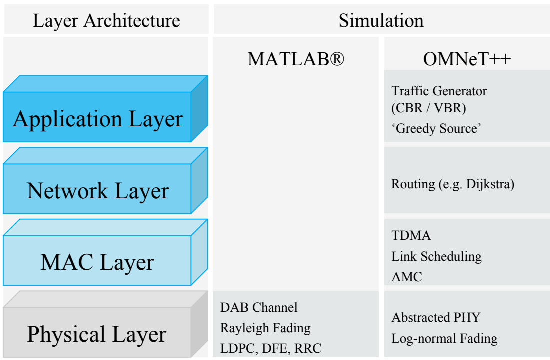


Fig. 3. The system model used for investigations and simulations.

optimal routing based on Dijkstras shortest path first algorithm [11], which is an algorithm that solves the shortest path problem for a single-source graph. The algorithm determines the shortest path between a source node and one (or all) sink node(s) for a graph with non-negative weighted edges. In our implementation, the edge weight (i.e. a certain cost function) is determined by the reciprocal of the number of symbols M for the modulation scheme used on a radio link (e.g. M=64 for 64-QAM, etc.). We disregard the fact, that a routing protocol produces traffic overhead. Furthermore, we assume the network to be in a steady state, so we investigate a 'snapshot' within the whole lifecycle of the network. From this point of view, we can also assume that the initial routes are already well-known at the time of our investigations.

As a relay scheme, we assume decode-and-forward (DF), based on the advantages in performance and flexibility [4], [12] as mentioned earlier. Within the simulation, optimal scheduling is assumed. In fact, we omit all signalling overhead for the network layer and the routing protocol as well as for the MAC layer and its cross-layer module for AMC.

The considered AMC algorithm as well as the thresholds are explained in detail in Part I of this study [13]. In fact, the AMC module adapts each link in a way to use the minimal MCS along a certain route. As a working hypothesis, we assume an ideal feedback channel with perfect channel knowledge. The structure of a TDMA-slot is shown in Figure 4.

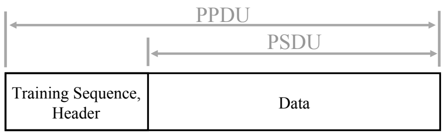


Fig. 4. Structure of a TDMA-slot.

B. *Simulations of the Physical Layer*

The simulation results of the physical layer provide packet error rates for different modulations and code-rates which are used to define SNR thresholds. These thresholds are input parameters of the simulation environment for the upper layers in order to choose an appropriate modulation and code rate according to the parameters of a radio link. Additionally, the PPDUs transmitted are influenced by a distance-dependent path loss model as well as an uncorrelated log-normal shadowing (sometimes referred to as 'slow fading', 'shadow fading', or 'long-term fading') while the impact of Rayleigh fading (sometimes referred to as 'fast fading' or 'short-term fading') is already considered in the results from [13].

V. Simulation Results

For each layer of the overall system level simulation, different parameters are defined, which are listed in Tables I and II. The general behavior of the simulation can be described as follows: by increasing d_{SD}, the SNR on the direct link between source and destination decreases until a specific point where a multi-hop transmission achieves a better performance. As d_{SD} increases, generally, multi-hop routes become more and more likely and AMC performes link adaptation according to the current SNR on the link. Within our model we have only one single source and sink node and also a fixed number of relay nodes (see Table I). The coordinates of the nodes deployed to the simulation area remain constant during a specific simulation run. To illustrate

TABLE I
Overall Simulation Parameters

Parameter	Value AWGN	Value DAB
$d_{99\%,\mathrm{BPSK1/2}}$	5336 m	2674 m
Simulation area	(4150 x 4150) m	(2080 x 2080) m
Number of nodes (s / r / d)	1 / 10 / 1	1 / 10 / 1
Node density D	$1.16 \cdot 10^{-6}$	$4.62 \cdot 10^{-6}$
Relay node distribution	Uniform	Uniform

the performance of multi-hop relaying combined with link adaptation, in the following we present selected simulation results, which have been obtained by evaluation of the output of the Monte Carlo computer simulations as described in the previous sections.

TABLE II
LAYER-SPECIFIC SIMULATION PARAMETERS

Layer	Parameter	Value
Physical	Transmission power	30 dBm
Physical	Path loss coefficent	3.5
Physical	Standard deviation log-normal shadowing	2.0 dB
Physical	Bandwidth	25.0 kHz
Physical	Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Physical	Code rate	1/2, 2/3, 3/4, 5/6
MAC	TDMA slot length	60 ms
MAC	TDMA frame length	180 ms
Network	Routing algorithm	Dijkstra SPF
Network	Routing metric	$1/M$

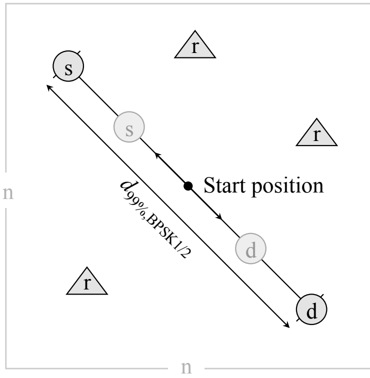


Fig. 5. General simulation scenario with increasing distance between the source and destination node d_{SD} over several simulation scenarios.

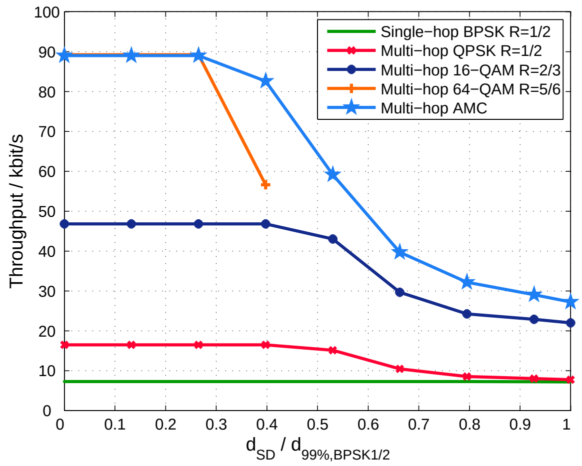


Fig. 6. Average end-to-end net throughput versus source destination distance d_{SD} for AWGN channel conditions.

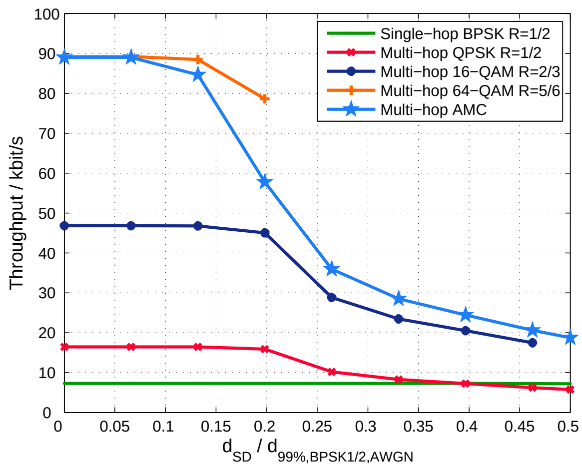


Fig. 7. Average end-to-end net throughput versus source destination distance d_{SD} for DAB channel conditions.

A. *End-to-End Net Throughput*

Figures 6 and 7 depict the average end-to-end net throughput over the distance between source and destination d_{SD} for both, AWGN and DAB radio channels. The maximum achievable data rate on the application layer is about 89 kbit/s using 64-QAM as modulation and 5/6 as code rate. As reference, the throughput for Single-hop BPSK 1/2 using a direct link is also shown. Since the simulated area depends on $d_{99\%,\text{BPSK1/2}}$ for each simulated radio channel, the abscissa is normalized to $d_{99\%,\text{BPSK1/2,AWGN}}$ for both diagrams.

For small distances d_{SD} Single-hop BPSK 1/2 achieves the lowest average end-to-end net throughput, whereas Multi-hop AMC and Multi-hop 64-QAM R=5/6 yield approx. the highest throughput achievable in the simulation. On the other hand, for large d_{SD} a more differentiated behavior is shown: for increasing d_{SD}, the throughput of all relaying schemes decreases and in case of AWGN radio channel, Multi-hop 64-QAM R=5/6 shows the steepest descend yielding approx. zero end-to-end net throughput. In contrast, for DAB radio channel conditions and small d_{SD}, Multi-hop 64-QAM R=5/6 achieves the highest throughput of all transmission schemes simulated. However, for $d_{\text{SD}} > 0.26$ and $d_{\text{SD}} > 0.13$ for AWGN and DAB, respectively, the corresponding PER exceeds the maximum acceptable value of $3*10^{-2}$. It is noted that the diagrams show theoretical values for Multi-hop 64-QAM R=5/6 although a transmission scheme exceeding PER $> 3*10^{-2}$ is regarded to be infeasible concerning the services assumed. In general, the diagrams are consistent with the hop counts depicted in Figures 8 and 9 for AWGN and DAB radio channels, respectively. It is noted that one reason for the decreasing throughput is the increasing transmission slots for routes using multiple hops.

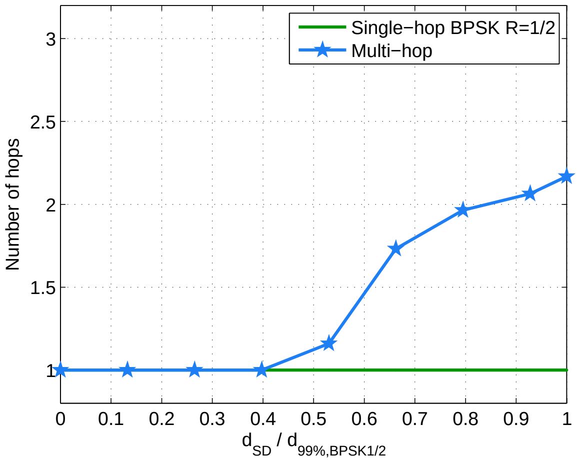


Fig. 8. Average hop count versus source destination distance d_{SD} for AWGN channel conditions.

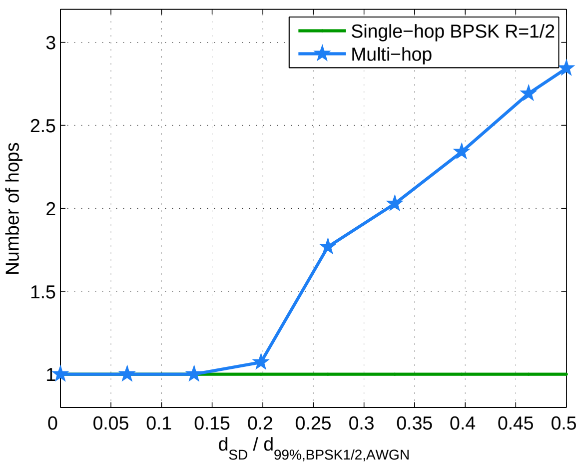


Fig. 9. Average hop count versus source destination distance d_{SD} for DAB channel conditions.

B. Packet Error Rate

The diagrams in Figures 10 and 11 depict the average packet error rate for the transmission schemes simulated. Multi-hop 64-QAM R=5/6 shows the most differentiated behavior while all other transmission schemes yield a PER of constantly lower than 3*10^{-2}. Despite the fact AWGN channels generally are less error-prone compared to DAB channels, the diagrams show, that the AWGN simulations achieve the maximum packet error rate. This behavior is caused by the decreased node density (see Table I) and therefore an increased average hop length in the case of AWGN radio channels. As mentioned earlier, Multi-hop 64-QAM R=5/6 yields PER larger than 3*10^{-2} for distances $d_{SD} > 0.26$ and $d_{SD} > 0.13$ for AWGN and DAB, respectively.

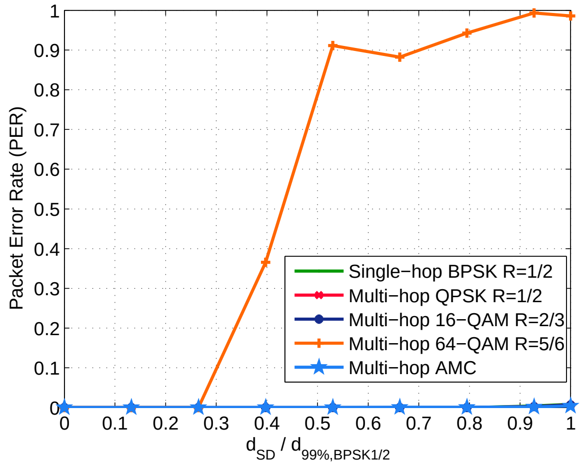


Fig. 10. Average packet error rate versus source destination distance d_{SD} for AWGN channel conditions. Note: Ter PER of all transmission schemes except Multi-hop 64-QAM R=5/6 are in the range of Single-hop BPSK R=1/2.

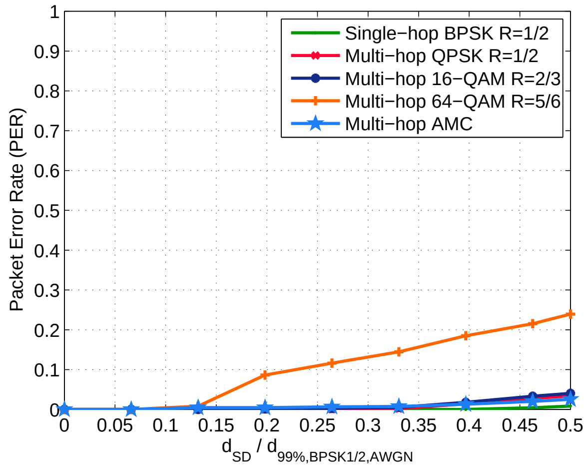


Fig. 11. Average packet error rate versus source destination distance d_{SD} for DAB channel conditions.

VI. Conclusions

In this paper the combination of AMC and relaying compared to a single-hop transmission and relaying only is investigated. Generally, the simulation results show that for the multitude of simulated d_{SD}, multi-hop using AMC achieves the best average throughput while satisfying the constraints regarding PER. The results confirm the ability of AMC in multi-hop networks to trade throughput for coverage and vice versa, which provides network designers with an additional degree of freedom when designing MANETs. For the evaluation of the simulation results, the thresholds used for the AMC algorithm defined in [13] strongly impact the throughput and PER performance and are an interesting topic for future research.

Furthermore we have introduced a simulation environment for Monte Carlo computer simulations based both on MATLAB® for a detailed physical layer simulation and OMNeT++ for the simulation of the whole system including all abstracted physical models and the upper layers as well.

A. Future Considerations

Future work comprises extending AMC to adapt the transmission parameters seperately on each link of a route in mobile ad-hoc networks. A further subject would be the optimization of the thresholds used for AMC according to specific application requirements.

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