Feedback Delay and its Impact on Adaptive Modulation and Coding in VHF Narrowband Mobile Ad-hoc Networks

Sebastian Helmle*†, Mathias Dehm*†, Michael Kuhn†, Dominik Lieckfeldt* and Dirk Pesch‡
*Rohde & Schwarz GmbH & Co. KG, Stuttgart, Germany
Email: sebastian.helmle@rohde-schwarz.com
†University of Applied Sciences Darmstadt, Darmstadt, Germany
‡Nimbus Research Centre, Cork Institute of Technology, Cork, Ireland

***Abstract*—Mobile ad-hoc networks (MANETs) enable operation without fixed infrastructure, making them attractive for disaster search and rescue (SAR) and tactical applications. Reliability is an issue in such applications and increasing MANET communication reliability is critical for the acceptance of these systems. In this paper we investigate the impact of feedback delay on adaptive modulation and coding (AMC) in VHF narrowband MANETs. We analyse communication reliability and quality of service (QoS) under realistic conditions and study user net throughput and packet delivery ratio (PDR) for various AMC feedback delays using Monte Carlo computer simulation. We show that feedback delays of multiple frame durations are tolerable even for higher velocities (300 km/h) without significant reliability issues, on the other hand for high delays the system trades throughput for reliability.**

Keywords*—*Mobile ad-hoc networks, adaptive coding.

I. Introduction

The vision of infrastructure-less communications with mobile ad-hoc networks (MANETs), which are able to provide communication services in a constantly changing network topology, has motivated considerable research effort over the past two decades. The advent of small, portable communication devices like personal digital assistants (PDAs), smartphones and tablets, and wearable computers is offering the potential to make this vision come true for application areas where

(i) only sparse or no infrastructure is provided,

(ii) nodes join, leave, and re-join the network by intention, due to mobility, or due to adverse effects of the radio channel,

(iii) and/or nodes are both concentrated at one location and sparsely distributed in other regions.

Applications such as disaster search and rescue (SAR) missions and tactical communications can use MANETs to establish and maintain connections between nodes as MANETs can operate in such conditions by adapting transmission parameters according to the changing network topology. However, while adaptation mechanisms such as adaptive modulation and coding (AMC) can significantly improve network performance, the deployment of these techniques is relatively complex in networks with completely distributed management. Especially in networks with strong bandwidth limitations as investigated here, the difficulty of increasing overhead emerges, requiring effective parameter adaptation in MANETs.

The subject of this paper is the investigation of the impact of feedback delay on AMC in narrowband (bandwidth of 25 kHz) MANETs, typically used in SAR and tactical communication systems.

The phenomenon of a delay in receiving feedback information may arise due to a variety of reasons such as occupation of resources owing to multiple use by other control information (resource reservation, routing information, etc.), delay caused by latency from signal processing, and QoS control mechanisms (e.g. queue control). Another reason for a delay may be the fact that the feedback information itself arrives without delay but some data packets have been already segmented and placed into the queue. Hence, the information gathered by the feedback information can not be considered for these packets. Usually, such a delay is a small single-digit multiple (zero to five) of the frame duration depending on the number of network participants and the frame configuration applied. Here, AMC is investigated at system level using an abstract model for the radio channel, with a delay spread of 14.5 μs. The results presented are based on a variety of feedback delays to analyse in which case an AMC closed loop system achieves reliable communication performance. Despite the fact that only single-hop transmissions are analysed, our findings can also be beneficial for quality of service (QoS) provisioning in (TDMA-based) multi-hop wireless radio communication systems employing AMC.

The remainder of this paper is organised as follows: Section II presents related work. The system model used in our study is described in Section III. In Section IV the simulation model and parameters as well as the results are presented. Finally, Section V concludes the paper.

II. Related Work

To mitigate multi-path fading impairments in two-hop MANET scenarios, adaptive modulation and coding can be applied as shown in [1]. The combination of AMC and multi-hop transmission can achieve a trade-off between network coverage and throughput. The authors of [1] provide a mathematical performance evaluation for two-hop connections (source - relay - destination). In 2008, Cho et al. investigated multi-hop networks for multicast broadcast services in mobile WiMAX systems [2]. For the optimisation of throughput, an AMC scheme was adopted in order to perform appropriate selection of modulation and coding schemes (MCS) between base station and relay station. As shown from computer simulations, the application of AMC to multi-hop networks with (fixed) infrastructure can yield significant performance improvements.

In [3] the impact of link adaptation in frequency-selective wireless multi-hop ad-hoc networks was investigated with respect to the average end-to-end throughput and delay. Here, only scenarios without mobility were considered. The benefits of using AMC were shown for both AWGN and DAB channel conditions. The results confirmed the suitability of AMC in trading throughput for coverage in multi-hop networks. However, the performance of a closed loop AMC system significantly depends on the thresholds for the modulation and coding schemes applied. Zheng et al. analysed the impact of AMC adjustment period in mobile satellite communications environments [4] and found that the application of AMC can improve the performance. However, they showed that for longer AMC adjustment periods the performance improvement will be less obvious.

Ekpenyong and Huang [5] investigated the limits of AMC and MIMO for frequency division duplex (FDD) systems. They found that a delay in feedback can be interpreted as reduced SNR. Furthermore, they observed that feedback error introduces an outage region where AMC is not feasible. To compensate for the impact of feedback delay channel prediction can be utilised. However, the effectiveness of channel prediction depends on the accuracy of the underlying channel model. Döttling et al. [6] evaluated the performance of channel quality feedback (CQF) schemes for High-Speed Downlink Packet Access (HSDPA) using FDD. Overall, they found that CQF schemes, considering data packets which are transmitted as bursts, enable notably higher efficiency compared to a cyclic AMC feedback. Furthermore, they mentioned that reducing the overhead caused by CQF saves power and mitigates interference.

In [7] the impact of feedback delay on single-hop networks employing AMC and selective repeat automatic repeat request (SR-ARQ) was investigated with respect to the average packet error ratio (PER) as well as the spectral efficiency. Overall, a system which takes into account feedback delay can improve the average PER. Hence, the authors conclude that only systems which consider feedback delay are able to meet QoS constraints. Despite a slightly reduced throughput, such systems show improved spectral efficiency. In [8] Yi et al. proposed an AMC feedback scheme for vehicular environments which is robust against feedback delay. In fact, applying the proposed scheme enables efficient reduction of impairments from temporal radio channel variations.

As shown here, studies investigating the impact of feedback delay exist. However, the related work does not deal explicitly with QoS from the AMC point of view, i.e. how the specific operation of queuing disciplines for QoS, resource reservation and assignment, etc. affect AMC performance. In most cases the underlying system models differ from the boundary conditions we consider here, e.g. narrowband channel, VHF radio, etc. For example, in satellite communication high propagation delays and low SNR at the receiver need to be considered whereas shadow fading is in general not a major impact factor except in cities with dense and high buildings. Mobile radio networks like UMTS achieve coverage by employing a cellular system with frequency reuse that leads to substantially higher user bandwidths (multiple MHz) compared to our narrowband VHF system. Since they are centrally organised (using base stations) only single-hop transmissions occur.

This paper contributes results from performance evaluation of AMC feedback delay in narrowband MANETs operating in the VHF frequency band and QoS requirements to guarantee an AMC based on feedback information achieves reliably good performance.

III. System Model

In this section the system model we have used in our study is described. We will clarify the entire model starting with some general information about the upper layers (based on OSI model) down to some of the physical layer specifics.

Our model is based on a very high frequency (VHF) narrowband mobile ad-hoc network consisting of two nodes. The first node is the source (S) which transmits data packets and the second node is the destination (D) which receives the data packets. Fig. 1 shows the scenario. Initially, the nodes are separated by a distance $d_{99\%,\text{BPSK1/2}}$. During our observations the source node moves directly towards the destination node with constant velocity $\overline{v}_{\text{Source}}$, which is a typical movement pattern for a SAR missions scenario. The source node generates

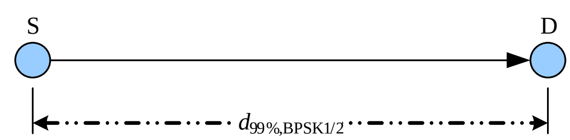

Fig. 1. System model and scenario.

two different types of data. The first type is a constant bit rate (CBR) or real time service such as voice calls or video streams. The second data service is a variable bit rate (VBR) service such as positioning data or background data transfer like maps or other non-real time data. In our study the application layer of the source node generates both a CBR and a VBR data stream in parallel. The application layer is implemented as a particular form of a greedy source, generating traffic continuously at the maximum achievable data rate. At low data rates at least the CBR data stream is transmitted. Whenever the data rate available is sufficient, the VBR data stream will also be transmitted in addition to the CBR service.

We assume the single-hop network to be in a steady state, as we investigate a 'snapshot' of the entire lifecycle of the network. Hence, we assume that routes are already well-known at the time of our observations, which enables the opportunity to isolate effects from feedback delay.

The link layer of our system model transmits data without any error-control mechanism such as automatic repeat request (ARQ). Consequently, when a data packet gets corrupted, no retransmission occurs which is a typical behaviour for real time applications. Time division multiple access (TDMA) is used to manage the channel access. The entire time frame structure is depicted in Fig. 2. As we consider multicast voice to be the most important service capable of reaching the majority of destinations within a single hop, slots are designed to accommodate voice packets even in the case the most robust transmission scheme is applied. Furthermore, we demand the system to be able to establish either three quasi-parallel single-hop channels or at least one multi-hop channel. We found that for our scenario three hops is sufficient to cover all destinations in the majority of cases. Hence, a TDMA frame consists of three slots for user data transmissions each with duration T_{S}. Each slot is followed by a short control minislot of duration T_{M} for the transmission of AMC feedback information and other control data. The frame duration T_{F} is defined to exactly correspond to the packet departure rate of the voice application. This avoids additional delays and jitter to meet QoS requirements.

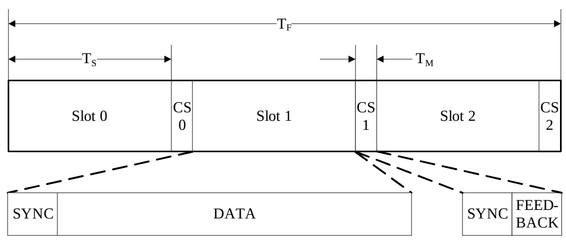

Fig. 2. TDMA frame structure consisting of data slots and control minislots (CS) for AMC feedback information and other control data.

We assume synchronisation to be perfect, i.e. no interference due to signals exceeding slot or minislot boundaries occurs. The TDMA is expected to be of completely distributed nature and hence no dedicated master handling resource reservation, etc. exists. Therefore a RTS/CTS (request to send/clear to send)-based reservation procedure like in [9] can be applied to achieve distributed behaviour. For each data packet of which at least the header is received correctly a short AMC feedback packet will be transmitted by the destination node to inform the source node which modulation and coding scheme (MCS) should be applied for the next packet. While the MCS for the data transmitted in regular slots is variable, AMC feedback information uses the most robust MCS exclusively.

In order to study the effect of feedback delay, we apply an AMC algorithm where MCS selection is based on signal-to-noise ratio (SNR) measurements for a received packet as well as on pre-defined SNR thresholds. The SNR may be obtained either by a channel estimation via the SYNC sequence prior to DATA or by computing the error vector magnitude (EVM) subsequently to the equalisation process. Fig. 3 depicts a SNR-based switching scheme in a qualitative manner. Thresholds are defined to satisfy a packet error rate $\leq 10^{-2}$ [10] and a variety of MCSs are supported as defined in Table I. However, the AMC algorithm supports switching only between adjacent MCSs, i.e. switching between, for instance, MCS 0 and MCS 4 (and vice versa) is not possible.

For the physical layer we assume a single-carrier system operating in the VHF band for long-range applications at carrier frequency f_{C} and with bandwidth B. Since our physical layer supports a variety of MCSs, the system is able to adapt its parameters according to the channel conditions. The physical layer is simulated in a detailed link layer simulation where look-up tables associating SNR with packet error ratio (PER) are generated for further use in our system level simulation. The link layer simulation is able to consider effects as Doppler spread, multipath propagation, synchronisation, frequency offset, channel estimation and equalisation as well as filtering and oversampling aspects [10].

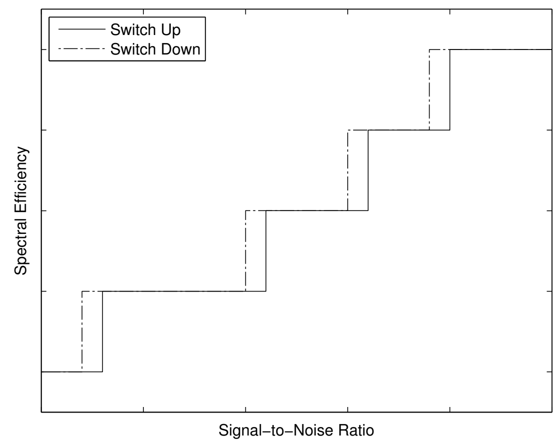

Fig. 3. Qualitative representation of thresholds for AMC.

TABLE I. SUPPORTED MODULATION AND CODING SCHEMES

MCS	Modulation	Code rate	MCS	Modulation	Code rate
0	BPSK	1/2	7	16-QAM	1/2
1	BPSK	2/3	8	16-QAM	2/3
2	BPSK	3/4	9	16-QAM	3/4
3	QPSK	1/2	10	16-QAM	5/6
4	QPSK	2/3	11	64-QAM	2/3
5	QPSK	3/4	12	64-QAM	3/4
6	QPSK	5/6	13	64-QAM	5/6

Signals transmitted by a node are affected by a distance-dependent path loss

$$\gamma\left(d(t)\right) = \alpha(d_0) + \eta \log\left(d(t)/d_0\right) + \theta \quad (1)$$

derived by Pugh et al. in [11], where $d(t)$ represents the separation of the source and destination node at time t, $\alpha(d_0)$ is the mean path loss at a given reference distance d_0 in the far-field of the transmitting node antenna, and η denotes the path loss exponent. The path loss also consists of fading due to shadowing and is represented by θ. In our system shadowing is modelled as a spatially correlated log-normal process with a standard deviation σ_{Link} and a decorrelation distance d_{Corr} to consider influences from buildings, hills, etc. which can eventually be exploited by the AMC algorithm. This implementation of shadowing is based on pre-generated maps like described in [12]. A channel with an exponential delay power profile and a propagation delay of 100 μs (i.e. a delay spread of 14.5 μs) applies as it was found that in the VHF band multipaths up to 100 μs may occur.

Several parameters relating to the radio channel and the physical layer have been taken from [13] as they are based on field measurements.

IV. Numerical Results

In the following, the results of our analysis are presented for a variety of both the velocity of the source node $\overline{v}_{\text{Source}}$ and the delay of the AMC feedback information. At first, as a reference, results are presented based on a priori knowledge of the SNR in order to select the optimal MCS. For the second scenario the destination node responds with an AMC feedback packet in control minislot $n + 1$ for each packet for which at least the header was decoded correctly in slot n. This represents the optimal case in a real system. In the last scenario AMC feedback information is sent delayed by an integer multiple K of the frame duration T_{F}, i.e. packet number j uses AMC feedback information from packet $j - K$. Thus, situations where a constant delay to the transmission of AMC feedback information occur are taken into account.

For each simulation run, the nodes are initially separated by $d_{99\%,\text{BPSK1/2}}$ and the source node moves towards the destination node (minimal distance: d_0) with a constant velocity $\overline{v}_{\text{Source}}$. Furthermore, we investigated the case where the source is departing from the destination node with a velocity of 300 km/h. In this case the maximum distance is $d_{99\%,\text{BPSK1/2}}$. To ensure the nodes operate within a range where AMC is effective $d_{99\%,\text{BPSK1/2}}$ is defined as the distance at which a connection can be successfully established in 99 per cent of all cases using the most robust MCS. In fact, for a reasonable shadowing margin, the distance $d_{99\%,\text{BPSK1/2}}$ has to be selected such that the system experiences a high probability of good SNR conditions (SNR > 15 dB).

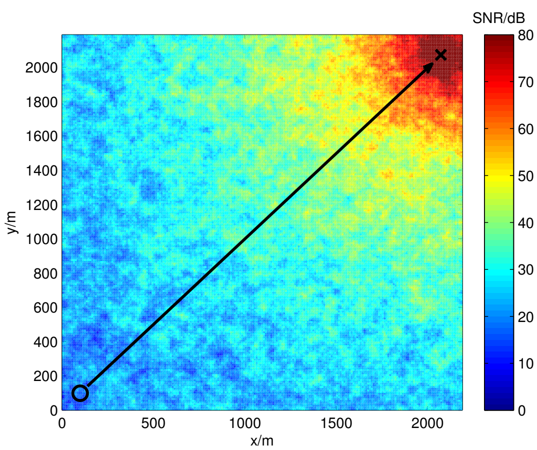

Fig. 4. Overview of simulation scenario; *o* and *x* represent the initial positions of the source and destination node, respectively.

In Fig. 4 a two-dimensional SNR map for one simulation run is shown as an example. The most significant parameters used for the computer simulations are given in Table II.

A. User Net Throughput

Fig. 5 depicts the average user net throughput versus AMC feedback delay for different velocities of the source node. In case of perfect a priori knowledge of SNR at the destination the average user net throughput at the application layer is about 20.17 kbit/s. While the structure of our TDMA frame enables the opportunity to establish three quasi-parallel data

TABLE II. Simulation Parameters

Parameter name	Parameter setting
Velocity source node $\overline{v}_{\text{Source}}$	$\{3, 10, 75, 300\}$ km/h
Path loss exponent η	4.25
Reference distance d_0	100 m
Intercept $\alpha(d_0)$	71.3 dB
Std. deviation shadowing per link σ_{Link}	5.12 dB
Decorrelation distance d_{Corr}	20 m
Transmission power p_{TX}	30 dBm
Carrier frequency f_{C}	57.0 MHz
System bandwidth B	25.0 kHz
Noise figure NF	6 dB
TDMA frame duration T_{F}	180 ms
TDMA slot duration T_{S}	52 ms
TDMA minislot duration T_{M}	8 ms

streams (cf. Fig. 2), the source node emits its signals only in slot number 0. Hence, the user net throughput corresponds to one third of the system net throughput. For slow velocities (i.e. 3 and 10 km/h), the impact of AMC feedback delay is negligible within the observed interval from 0 to 100 frames, which is a result of good SNR conditions in our scenario (cf. Fig. 4). For velocities of 75 and 300 km/h, respectively, a

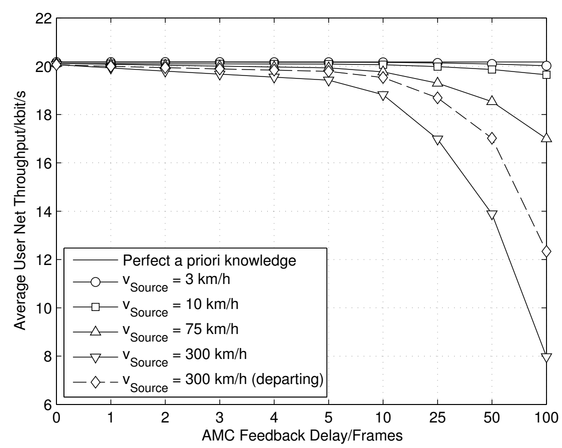

Fig. 5. Average user net throughput versus AMC feedback delay.

decrease in throughput for increasing AMC feedback delays can be observed. This behaviour is based on the fact the higher the feedback delay the lower is the average MCS (cf. Fig. 6). Since our AMC aims for a packet delivery ratio (PDR) ≥ 0.99, a delay in feedback increases the probability that a more robust MCS is used for a longer period unless channel conditions improve due to a decrease in distance between source and destination node. In contrast, in case of the departing scenario we observe better throughput since high-order MCSs are used for a larger amount of time. This is also evident from the average number of bits per symbol (cf. Fig. 6).

B. Packet Delivery Ratio

The average PDR, which is defined as (1-PER), is depicted in Fig. 7. At first, it can be noted that for all combinations of source node velocity and AMC feedback delay a minimum PDR of 0.99 is obtained, which is a result of suitably chosen AMC thresholds. Although the behaviour is as expected as for

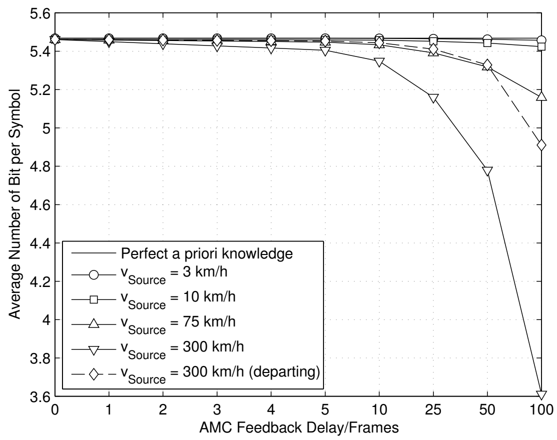

Fig. 6. Average number of bits per symbol (coding not considered) versus AMC feedback delay.

velocities of 3 and 10 km/h, the results for higher velocities have to be discussed more specifically. As shown, for an AMC

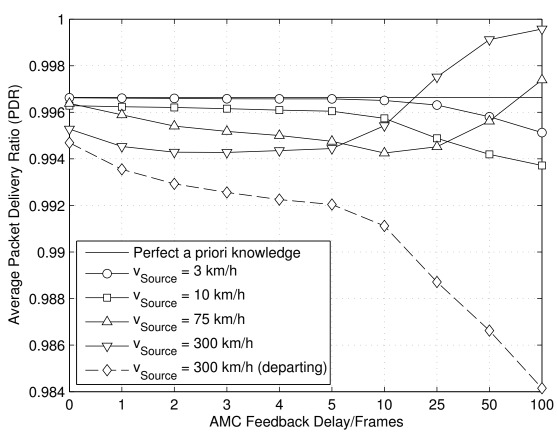

Fig. 7. Average packet delivery ratio (PDR) versus AMC feedback delay.

feedback delay > 5 frames, PDR performance improves. More importantly, at a certain point the PDR for these two velocities achieves better performance than AMC having perfect a priori knowledge of SNR conditions. This can be explained as follows: As the distance between source and destination node decreases, SNR conditions improve due to a decreasing free-space attenuation. However, for large feedback delays the update of the modulation and coding scheme will be delayed proportionally. Therefore the MCS will remain at a lower order (e.g. BPSK instead of 16-QAM) although the radio channel conditions are sufficient for higher order MCSs. This leads to a more robust overall transmission with higher PDR on one hand and lower number of bits per symbol on the other hand (cf. Fig. 6). To understand this counter-intuitive effect it is essential to note that in this scenario the most robust MCS applies as the initial state. Hence, a large number (i.e. the first 100) of packets, are using the most robust MCS prior to the arrival of the first feedback packet where the MCS can be adjusted for the very first time.

V. Conclusions

In this paper the impact of feedback delay on adaptive modulation and coding in a single-hop VHF narrowband MANET has been investigated. In general, results from computer simulations show a negative impact on the average user net throughput for joint node velocities $\geq$ 75 km/h as AMC feedback delay exceeds the duration of ten frames. However, applying an AMC mechanism with appropriate thresholds, the packet delivery ratio does not drop below 99 per cent, which is sufficient for many data transmission services. As we found, for our setup and for small delays the impact on system performance is negligible small even for velocities up to 300 km/h. Hence, the phenomenon of feedback delay remains more a theoretical issue rather than a practical challenge assuming a maximum delay of five frames for feedback information.

References

[1] A. Müller and C. Y. Hong, “Dual-hop adaptive packet transmission systems with regenerative relaying,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 1, pp. 234–244, 2010.

[2] C. H. Cho, K. T. Kim, and Y. Y. Hee, “Mobile multi-hop relay system using AMC for multicast broadcast service over mobile WiMAX,” in *Wireless Telecommunications Symposium, 2008. WTS 2008*, 2008, pp. 46–52.

[3] S. Helmle, M. Dehm, M. Kuhn, D. Lieckfeldt, and D. Pesch, “The Impact of Link Adaptation in Narrowband Frequency-selective Wireless Ad-hoc Networks - Part II: The Network Perspective,” in *Proceedings of the 7th Karlsruhe Workshop on Software Radios*, 2012, pp. 66–71.

[4] W. Zheng, S. Ren, X. Xu, Y. Si, J. Chen, and J. Wu, “Impact analysis of AMC adjustment period in mobile satellite communications environment,” *2012 International Conference on Information Science and Technology (ICIST)*, pp. 802–805, 2012.

[5] A. E. Ekpenyong and Y.-F. Huang, “Feedback Constraints for Adaptive Transmission,” *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 69–78, 2007.

[6] M. Döttling, B. Raaf, and J. Michel, “Efficient channel quality feedback schemes for adaptive modulation and coding of packet data,” *2004. VTC2004 Fall. 2004 IEEE 60th Vehicular Technology Conference*, vol. 2, pp. 1243–1247, 2004.

[7] H. Dandan, X. Junfeng, Z. Shihong, and C. Shiduan, “Impact of Feedback Delay on System Performance with AMC/SR-ARQ over Rayleigh Fading Channels,” *Networking and Mobile Computing Wireless Communications*, pp. 1–5, 2006.

[8] W. Yi, C. Qimei, T. Xiaofeng, and Z. Mingyu, “Robust AMC Scheme Against Feedback Delay in Vehicular Environment,” *2009. ICC ’09. IEEE International Conference on Communications*, pp. 1–5, 2009.

[9] S. Haavik and B. Libæk, “Link Layer Design for a Military Narrowband Radio Network,” 2010.

[10] M. Dehm, S. Helmle, M. Kuhn, C. Körner, and D. Pesch, “The Impact of Link Adaptation in Narrowband Frequency-selective Wireless Adhoc Networks - Part I: The Physical Perspective,” in *Proceedings of the 7th Karlsruhe Workshop on Software Radios*, 2012, pp. 61–65.

[11] J. A. Pugh, R. J. C. Bultitude, and P. J. Vigneron, “Propagation Measurements and Modelling for Multiband Communications on Tactical VHF Channels,” *2007. MILCOM 2007. IEEE Military Communications Conference*, pp. 1–7, 2007.

[12] S. Helmle, M. Dehm, M. Kuhn, D. Lieckfeldt, and D. Pesch, “A Resource Efficient Model of Spatially Correlated Shadowing in Semi-Mobile Ad-hoc Network Simulations,” in *UKSim 15th International Conference on Computer Modelling and Simulation, UKSim2013 (UKSim2013)*, Cambridge, United Kingdom, 2013, pp. 645–649.

[13] L. Li and T. Kunz, “Efficient mobile networking for tactical radios,” *2009. MILCOM 2009. IEEE Military Communications Conference*, pp. 1–7, 2009.