Efficient Feedback Mechanisms in Mobile Narrowband Multicast Scenarios

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***Abstract*—Link adaptation algorithms are utilized in communication systems to increase the spectral efficiency or robustness by adapting transmission parameters to the channel conditions. Closed-loop link adaptation requires feedback from the receivers which can lead to high signalling overhead especially in multicast/broadcast communications. In this paper, two efficient feedback mechanisms for link adaptation in multicast/broadcast service are proposed and investigated in a mobile ad-hoc network (MANET) for search and rescues missions. The constraint on the system is to transmit two service classes in parallel, voice and data. Considering intelligibility of voice transmissions in multipath channels, the proposed mechanisms outperform state-of-the-art feedback mechanisms in nearly all considered mobile multicast scenarios. Compared to a full feedback report approach, the proposed mechanisms yield an increase in the amount of additional successfully transmitted bits by 32% while meeting low outage constraints.**

***Keywords*—Mobile ad hoc networks, narrowband, multicast communication, feedback, adaptive algorithm.**

I. Introduction

Mobile ad-hoc networks (MANETs) provide flexible, resilient and infrastructureless communications. Due to these advantages, MANETs have recently gained increased interest for search and rescue (SAR) missions and by organisations involved in security tasks. In these application scenarios wireless networks have to cope with connectivity over long distances in harsh environments (terrain features). Therefore, narrowband systems in the HF/VHF band are utilized. The primary application of these systems is voice transmission to multiple receivers (multicast/broadcast) in form of a constant bit rate (CBR) service. The requirements of this service differ from the voice service in civil communication systems in that civil communication systems are optimized with respect to voice quality whereas the most important requirement in SAR missions is intelligibility of voice by all receivers in the multicast group. These systems generally employ robust narrowband vocoders, which in principal provide only limited voice quality (e.g. MELPe - enhanced mixed-excitation linear prediction). Typical communication patterns in SAR missions are short commands or descriptions with a duration of a few seconds [1]. Previous investigations have shown that the packet error rate (PER) has significant impact on the intelligibility. According to [2], [3] for high intelligibility, the PER should be below 5% since retransmissions cannot be applied due to the real-time characteristic of the voice service.

Besides voice transmissions, position information, sensor data, bulk data etc. are emitted by the transmitter, hereinafter referred to as source node, as a variable bit rate (VBR) service in these networks [4]. Common narrowband systems provide only low data rates due to the limited bandwidth. To increase data rates, transmission parameters such as modulation and code rate are adapted with respect to the channel conditions. A closed-loop link adaptation algorithm requires feedback from the receiver, hereinafter referred to as destination node, about the current channel quality. Whereas in unicast communications the feedback is transmitted by a single destination node, multicast and broadcast services (MBS) suffer from an increase of feedback messages for link adaptation. This is known as the feedback implosion problem [5]. In some scenarios the gain in spectral efficiency is lost to the additional overhead incurred by feedback. In order to avoid feedback implosion in multicast communications, the narrowband waveform (NBWF) of the North Atlantic Treaty Organization (NATO) uses only a single robust modulation and coding scheme (MCS) for both, voice and data transmissions [6].

In this paper, we propose two efficient feedback mechanisms for link adaptation to increase the data rate of the VBR service in harsh environments for mobile multicast networks while high intelligibility of voice transmissions is maintained. Different feedback mechanisms are investigated by means of simulations and compared with respect to outage rate and additional data rate.

II. Related Work

The feedback implosion problem has been known for quite some time. However, the problem has gained increased attention in recent years since many applications rely on multicast or broadcast communications.

In [7] a timer-based feedback mechanism is proposed. After detecting a feedback request from the source node, multicast destination nodes schedule an exponentially distributed timer. When the timer expires in a destination node, the node transmits a message to the source if no other destination node's feedback message has been received beforehand. In case a feedback message has been received from another destination node, the feedback will be suppressed. Byung et al. propose an efficient multicast mechanism to transfer automatic repeat request (ARQ) [8] as well as link adaptation [4] feedbacks from all destination nodes to the source node via orthogonal frequency-division multiple access (OFDMA) under consideration of an IEEE 802.11a physical layer. Hereby, each destination node transmits feedback messages on different subcarriers.

In [9], multiple destination nodes transmit their feedback in a round-robin fashion. The number of feedback cycles increases with the number of nodes. Based on the feedback, the required MCS is determined and stored in a table in the multicast source node. The minimum required MCS in the table is then used for the next packet transmission. The transmission of feedback information can be further minimized using a selected or clustered round-robin approach. Initially, a round-robin over all nodes is performed to form a set of disadvantaged nodes. These selected destination nodes transmit feedback for a predefined period until a new set of disadvantaged nodes is determined.

Selective reporting is considered in [10], where feedback nodes are selected based on the path-loss, geometry or block error rate (BLER) in a cellular network. The nodes with the largest path-loss, geometry value or highest short-term BLER build a feedback set. The path-loss is measured in the link from the destination nodes to the base station. The geometry-based algorithm relies on the signal to interference plus noise ratio (SINR) excluding fast fading. The geometry value is reported by the destination nodes to the base station at a slow rate (1 Hz). The short-term BLER is calculated by the ACK/NACK from the hybrid ARQ mechanism. The three proposed metrics require a full report from the nodes (directly or in a defined rate) to form a set of feedback nodes. For a time division multiple access (TDMA) structure, full report requires additional pre-reserved slots in a super frame structure. Furthermore, the selected nodes need to be informed about the current set of feedback nodes. The additional signalling overhead and the more complex frame structure are disadvantages of selective feedback mechanisms.

Sohn et al. propose a state machine in each destination node for multicast communication [5]. The scheme considers three states: (1) feedback state (feedback), where the nodes transmit feedback until a predefined QoS requirement is satisfied i.e. frame error rate, (2) flag state, at which only one bit is transmitted to indicate to the base station to use the MCS from the previous frame, and (3) non feedback state (NFB) in case no frame error occurs. The proposed scheme outperforms the selective reporting mechanism based on BLER or geometry value in an LTE simulation environment. However, the number of transmitted feedback varies.

For a cellular system, the authors of [11] propose an anonymous common feedback channel where destination nodes send identical information on the same resource in a code division multiple access (CDMA) system. Destination nodes transmit a negative ACK (NACK) (two logical states, 0/1) indicating the dissatisfaction to a specific feedback condition. The base station increases transmission power upon receipt of the first NACK after transmission parameters have been adjusted. In case a NACK is detected for the next packet, the MCS is downgraded. This means that at least two successive NACKs need to be lost for a wrong MCS selection. In the investigated scenario, multipath fading, intra-cell interference and shadowing have been neglected. For more than five destination nodes, the NACK feedback mechanism still increases the performance in spectral efficiency and coverage compared to a fixed MCS.

State-of-the-art feedback mechanisms for multicast communication have high overhead and complexity or achieve only low data rates. Especially in narrowband communication with a strict requirement on low overhead, algorithms relying on continuous up- and downlink transmissions as in broadband systems cannot be applied. Furthermore, related investigations primary focus on cellular networks instead of MANETs. Similar to [11], we propose two efficient feedback mechanisms transmitting feedback in the same resource, i.e. time and frequency. In contrast to [11], our proposed mechanisms provide a three state feedback for a smooth link adaptation. The performance is investigated in a single-carrier narrowband TDMA system operating in a MANET with harsh environments like mobile multicast scenarios with multipath channels.

III. Reference Model

This section briefly describes the reference model containing the single-carrier narrowband transmission chain with a multipath channel model and the link adaptation algorithm.

A. Narrowband physical layer transmission chain

The reference model of the narrowband physical layer transmission chain is shown in Fig. 1.

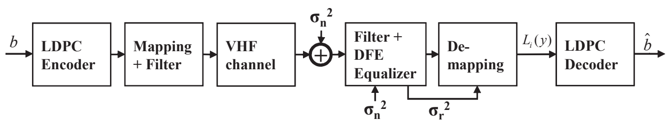


Fig. 1. Physical layer transmission chain - b: information bit sequence, σ_n^2: noise variance, σ_r^2: estimated residual noise, $L_i(y)$: log-likelihood ratios, $\hat{b}$: received bit sequence.

The physical layer consists of an irregular quasi-cyclic low-density parity-check (LDPC) encoder and decoder according to [12], M-QAM mapper and demapper, root raised cosine (RRC) transmit and receive filter for single-carrier transmissions and a T/2-spaced finite-impulse-response (FIR)-minimum mean-square error (MMSE) decision-feedback equalizer (DFE). A frequency-selective block fading channel model is considered with a root mean square delay spread σ_{T_m} of 14.5 μs in the VHF band. The channel is modelled as a wide sense stationary uncorrelated scattering (WSSUS) process with a uniformly distributed phase, an exponentially distributed delay and a Doppler frequency spread according to Jakes spectrum [13]. We assume a time-invariant channel during a burst (block fading) as well as perfect knowledge of the channel impulse response at the receiver. The narrowband system considers a bandwidth of 25 kHz with a time division multiple access (TDMA) slot structure. Each slot has a duration T_S of 90 ms.

Additional to voice as a CBR service, VBR services are transmitted in the same slot. The number of additional bits for the VBR service depends on the applied MCS and the size of the feedback slots. We use four different MCSs in this study. Figure 2 illustrates the packet error rate (PER) after the channel decoder over the root mean square (RMS) error vector magnitude (EVM) for the four MCSs. The root mean square EVM is determined after equalization in the receiver given by:

$$\mathrm{EVM_{RMS}} = \sqrt{\frac{\sum_{v=1}^{O} |S_{equ}(v) - S_{ref}(v)|^2}{\sum_{v=1}^{O} |S_{ref}(v)|^2}}\,, \tag{1}$$

where O is the number of symbols within the measurement period, $S_{equ}(v)$ is the normalized sample for the v^{th} symbol after equalization, $S_{ref}(v)$ is the normalized ideal reconstructed symbol by the receiver for the v^{th} symbol.

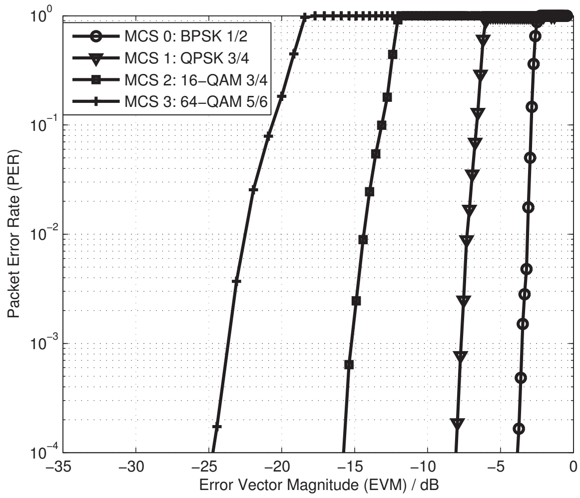


Fig. 2. PER of the considered narrowband system versus root mean square error vector magnitude (EVM).

The total path loss is given by

$$\gamma\left(d(t)\right) = \alpha(d_0) + \eta \log\left(d(t)/d_0\right) + \theta \quad \text{for} \quad d(t) > d_0, \tag{2}$$

where $d(t)$ is the distance between source and destination node, $\alpha(d_0)$ represents the mean path loss at a given reference distance d_0 in the far-field of the transmitter antenna, η denotes the path loss exponent and θ the path loss due to slow fading (shadowing). The chosen parameters for the path loss model have been determined from field measurements in the VHF frequency band [14]. Shadowing (slow fading) is modelled as a spatially correlated log-normal process according to [15] with a standard deviation σ_s and a decorrelation distance d_{corr}. The chosen parameters are listed in Table I.

B. Link Adaptation Algorithm

The link adaptation algorithm considered here decides on the required MCS according to EVM thresholds of each received packet. The EVM thresholds are defined to achieve a mean PER $\leq 10^{-2}$. The destination nodes signal a decrease (DOWN), keep (KEEP) or increase (UP) of the MCS to the source node. The source node chooses the lowest required MCS to satisfy a specific QoS requirement i.e. a target PER to guarantee intelligibility of the voice transmission. For example, if the source node receives a DOWN and a KEEP from the destination nodes, it decreases the MCS. In case a KEEP and an UP has been received, the MCS will not be changed. Only if all nodes require an UP, the MCS is increased.

IV. Reference Feedback Mechanisms

In this section we describe the multicast feedback mechanisms that we use as a benchmark for our own proposal. Feedback information is transmitted in a T_{FB} slot (as shown in Figure 3) using a 17 symbol Zadoff-Chu sequence. This approach is used in all feedback mechanisms considered here in order to achieve equal conditions for comparison. The three link states, i.e. DOWN, KEEP and UP, are represented by a different root sequence. Each destination node has its dedicated feedback slot to transmit one of these sequences. The requested link state is detected by the source node by calculating cross correlations of the received signal with each feedback sequence and deciding on the largest peak. For our investigation we assume that synchronization of the feedback is accurate within ± 1 symbol.

A. Fix MCS

Current mobile communication systems (e.g. NBWF [6], CDMA2000 1xEV-DO [16]) utilize a fixed MCS for multicast communications. According to NBWF, a robust MCS is utilized for data communications. A fixed MCS requires no feedback for link adaptation but might limit the amount of additional bits available for the VBR service.

B. Full Report

Full report (FR) is the reference mechanism where each destination node transmits its feedback in a separate slot after a packet has been received. In general, the TDMA structure is predefined i.e. for full report, the number of available feedback slots is equal to the number of maximum multicast destination nodes N_m (see Figure 3). In this approach, link state information of all nodes is available to determine the minimum MCS.

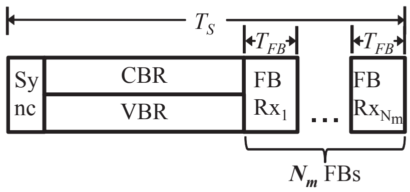


Fig. 3. Full report with N_m feedback slots.

C. Round-Robin

In round-robin (RR), destination nodes transmit feedback information in an alternating way. The cycle starts over again after each destination node in the multicast group has transmitted its feedback. It is assumed that the nodes have perfect knowledge of their positions in the cycle. Two variations of round-robin are investigated: (1) MCS is changed immediately according to the link state in the received feedback (Pure Round-Robin), and (2) a buffer of size of the multicast group is used to determine the minimum required MCS in the buffer (Buffered Round-Robin) as described in [9]. The buffer is initialized with the lowest MCS (MCS 0) and updated according to the feedback from the destination nodes. The feedback DOWN decreases and UP increases the MCS index in the buffer. The buffer is reinitialized with the index of the currently applied MCS after transmission parameters have been changed. The TDMA frame structure for round-robin requires only one feedback slot as shown in Figure 5.

V. Proposed Feedback Mechanisms

In this section, two feedback mechanisms are proposed to achieve full report with reduced overhead considering a single-carrier system for MANETs. The proposed mechanisms are similar to [11] where multiple destination nodes transmit feedback in the same resource, i.e. time and frequency. In contrast to [11], the proposed approaches distinguish between three link states instead of two for a smooth link adaptation. Furthermore, our approach instantly adapts the MCS without previous adaptation of the transmission power.

The following two link states are transmitted: DOWN and KEEP. The state UP is communicated implicitly when no DOWN or KEEP has been detected. The source node performs a cross correlation of the link state sequences and the received signal. The detection probability of the transmitted sequences suffers from multiple access interference (MAI). In contrast to the detection algorithm described in Section IV, this is more challenging since the source node has to detect if any DOWN or KEEP sequence has been transmitted rather than deciding which of the three link state sequences has been applied.

A. Full Report with Multi-Access Feedback Slots

In the first proposed mechanism using full report with two separate feedback slots (FR-2Slot) all destination nodes requiring a lower MCS transmit a feedback sequence in the DOWN-slot. The same approach applies for the KEEP state as shown in Figure 4. For both link states (DOWN and KEEP), Zadoff–Chu sequences with length 17 symbols are used.

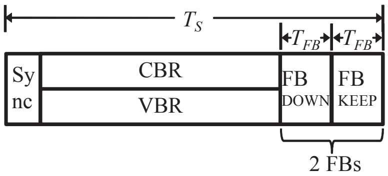


Fig. 4. TDMA slot structure of the proposed FR-2Slot mechanism.

B. Full Report with Orthogonal Sequences

The second proposed mechanism (FR-Orthogonal) uses orthogonal sequences for the link adaptation states DOWN and KEEP. Orthogonality is achieved by cyclic shifts of the Zadoff–Chu sequences. The cross correlations are performed with the two sequences and the received signal. In contrast to FR-2Slot, the proposed FR-Orthogonal mechanism requires only one feedback slot, as shown in Figure 5.

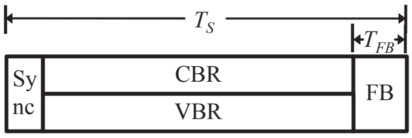


Fig. 5. TDMA slot structure of the proposed FR-Orthogonal mechanism.

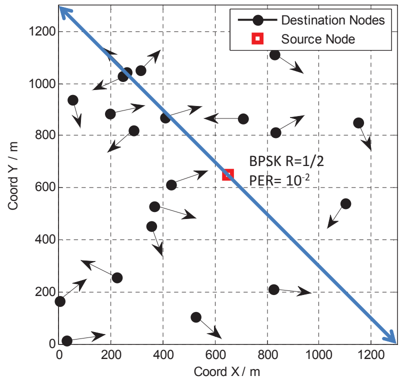


Fig. 6. Movement model with 20 Rx nodes.

TABLE I. Simulation Parameters.

Parameter name	Value
Transmission power	0 dBm
Symbol duration T	50 μs
Carrier frequency f_C	57.0 MHz
RMS delay spread σ_{Tm}	14.5 μs
Path loss exponent η	4.25
Reference distance d_0	100 m
Intercept $\alpha(d_0)$	71.3 dB
Std. deviation shadowing σ_s	5.12 dB
Decorrelation distance d_{corr}	20 m
Number of destination nodes N	$\{5, 20\}$
Max. number of destination nodes N_m	20
Velocities of destination nodes	$\{3, 120\}$ km/h
TDMA slot duration T_S	90 ms
Single TDMA feedback slot duration T_{FB}	1 ms
TDMA frame duration T_F	180 ms
Bit rate of the CBR service	2.78 kbit/s
Simulation area	1300 m x 1300 m
Simulation runs	1,000 runs, with 100 packets each

VI. Simulation Setup and Numerical Results

This section describes the simulation setup and parameters including the considered mobility model. Then the numerical results are presented and discussed in regard to the outage rate and the additional goodput.

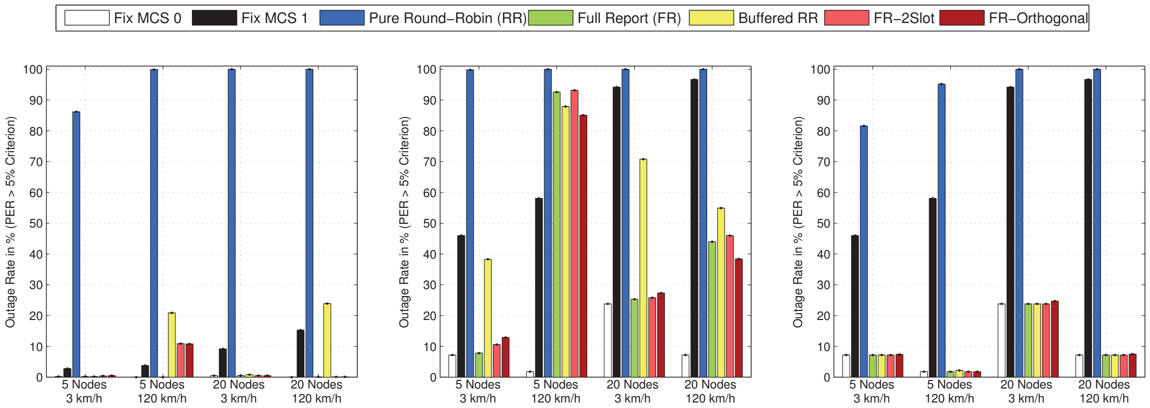
A. Simulation Setup

The destination nodes are moving around the simulation area according to the random direction mobility (RDM) model. When nodes hit the edge of the simulation area, they are reflected based on the incoming angle. Figure 6 shows an example scenario. The positions of the destination nodes in the simulation area and the movement angles are chosen randomly according to a uniform distribution. The source node has a fixed position in the centre of the simulation area to achieve a continuous coverage for the investigations. All destination nodes are moving with equal velocity.

Correlated shadowing with a decorrelation distance d_{corr} is used in all scenarios. With the consideration of shadowing, the source node output power is able to cover the corners of the simulation area with a probability of 99% when using the most robust MCS. However, multipath effects are neglected for the definition of the simulation area.

B. Numerical Results

In contrast to civil communication systems striving for high voice quality, for SAR communication systems high

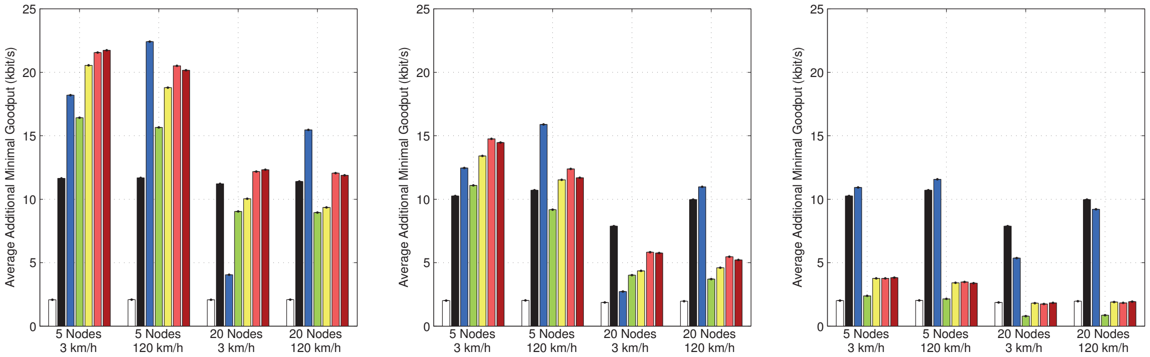


(a) AWGN channel

(b) Multipath channel

(c) Multipath channel with 10 dB offset on switching thresholds

Fig. 7. Outage rate for PER $> 5\%$ in AWGN and multipath channels for different scenarios (velocities and number of destination nodes).



(a) AWGN channel

(b) Multipath channel

(c) Multipath channel with 10 dB offset on switching thresholds

Fig. 8. Average additional minimal goodput in AWGN and multipath channels for different scenarios (velocities and number of destination nodes).

intelligibility of voice is the major requirement. According to [2], [3], high intelligibility of voice requires a PER less than 5%. Therefore, in our investigation an outage occurs when at least one node in the scenario exceeds a PER of 5% during a voice transmission of length 100 packets (18 s duration). All described feedback mechanisms are studied based on this specific requirement for voice communication.

Furthermore, the additional minimal goodput for different velocities and number of destination nodes are shown. The additional minimal goodput is defined as the minimum number of successfully received VBR bits over all nodes during a voice transmission. This goodput is averaged over all simulation runs and denoted as average additional minimal goodput. The performance of the feedback mechanisms are compared in two channel environments, an AWGN channel and a multipath channel, both with correlated shadowing.

1) Outage Rate: Figure 7a and 7b show the outage rates for both channel environments and different scenarios. In general, at low velocities nodes suffer from areas with deep fades for a longer time. For high velocities, the channel conditions change continuously requiring a fast reaction of the link adaptation algorithm.

The results for AWGN in Figure 7a show that most of the considered feedback mechanisms result in low outage rates. However, pure round-robin has very high outage rates for all scenarios which are due to the fact that the MCS is adjusted only according to the feedback from the currently selected destination node. Buffered RR suffers in scenarios with fast channel fluctuation and the outage rate increases with the duration of the feedback cycles. The results for the multipath environment shown in Figure 7b illustrate that the outage rates are significantly higher due to fast fading. Again, the outage rate increases with velocity. However, outage for buffered RR is remarkably high in the 20 nodes / 3 km/h scenario and decreases for higher velocity. This can be explained by the long duration of the feedback cycle and the slow channel fluctuations resulting in consecutive packet errors in case a node enters an area with a deep fade. Fixed MCS using the most robust MCS (Fix MCS 0) benefits especially from situations of fast channel fluctuations. The outage rate of the proposed FR-2Slot mechanism is similar to full report for different velocities and number of destination nodes. FR-Orthogonal has a slightly higher outage rate for slow velocities and a lower outage rate for high velocities compared to FR-2Slot. This can be explained by a reduced detection probability of the minimum link state for the orthogonal mechanism. However, independent from the feedback mechanisms, the outage rate is affected by fast fading in combination with the inert link adaptation.

2) Average Additional Minimal Goodput: Figure 8a shows that link adaptation increases the additional goodput compared to a fixed MCS for small multicast groups. It can be seen that all feedback mechanisms relying on link adaptation achieve huge increases in average additional minimal goodput compared to fixed MCS 0. Also, pure round-robin performs well in terms of goodput, however the highest additional goodput for node speeds of 120 km/h with 5 and 20 nodes is at the expense of high outage rates. In multipath environments, the additional goodput is slightly lower as depicted in Figure 8b. In both environments and all scenarios, FR-2Slot and FR-Orthogonal perform very well and are able to increase the additional goodput by about 32% compared to full report while having comparable outage rates. In comparison to the feedback mechanism in [9], here named as buffered RR, the additional goodput is increased in multipath channels with 5 nodes for FR-2Slot and FR-Orthogonal in average of about 9% and 5%, with 20 nodes in average of about 26% and 23% while the outage rates are reduced in nearly all scenarios. A maximum gain of nearly 33% is achieved with 20 nodes / 3 km/h for FR-2Slot and FR-Orthogonal.

C. Robust Multipath and Shadowing Simulation

The outage rates of the mechanisms relying on link adaptation are significantly above 10% for scenarios with node speeds of 120 km/h in the multipath environment. This might be too high for a reliable voice communication system. An approach to mitigate these high outage rates is to modify the switching thresholds of the link adaptation algorithm. This has been investigated by adding an offset of 10 dB to the switching thresholds. The simulation results in Figure 7c show the decrease in outage.

However, the results differ from the outage rates shown in Figure 7b where higher velocities lead to an increase of outage. This effect has already been discovered for fixed MCS in multipath channels with shadowing and low velocities. At low velocities, nodes remain in fades for a longer duration which results in a higher outage rate compared to high velocities. Except for fixed MCS 1 and pure round-robin, all feedback mechanisms achieve an outage rate similar to MCS 0, which is the most robust MCS and hence defines the minimum outage rate. As shown in Figure 8c, modifying switching thresholds reduces the goodput. However, FR-2Slot and FR-Orthogonal still have much higher goodput compared to full report while yielding nearly the same outage rate.

VII. CONCLUSION

This paper has proposed two mechanisms for efficiently transmitting feedback information for link adaptation in mobile multicast scenarios. For both mechanisms, nodes transmit feedback information using the same resources (i.e. time and frequency) in a single-carrier narrowband system. The first proposed mechanism applies two separate feedback slots for the link states DOWN and KEEP. The second mechanism requires only one feedback slot and uses two orthogonal sequences to distinguish between both link states. The performance is compared to state-of-the-art mechanisms (i.e. pure round-robin, buffered round-robin and full report) with respect to outage rates for high intelligibility of voice and additional successfully transmitted information bits (goodput). The investigation considered different environments, e.g. AWGN and multipath channels with shadowing. Multipath channels typically exist in the harsh environments experienced in search and rescue missions. The proposed mechanisms have the capability to increase the additional goodput by about 32% in comparison to full report with nearly the same outage rate. Furthermore, comparing the results with buffered RR, the additional goodput is increased up to 33% while the outage rates are reduced in nearly all scenarios for AWGN and multipath environments. Both suggested feedback mechanisms FR-2Slot and FR-Orthogonal provide similar performances with respect to the outage rates and additional goodput. The results show that feedback can be transmitted using same resources by different nodes. This approach might also be suited for ACK/NACK feedback used in hybrid ARQ (HARQ).

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