Feedback interval for link adaptation in TDMA-based single-carrier VHF narrowband mobile ad-hoc networks

S. Helmle, M. Dehm, M. Kuhn, D. Lieckfeldt and D. Pesch

The impact of a link adaptation feedback interval on user net throughput for time division multiple access (TDMA)-based single-carrier very high frequency (VHF) narrowband mobile ad-hoc networks (MANETs) is investigated. Specifically for the narrowband MANETs optimisation of the signalling overhead is one of the major challenges. Reducing the overhead means that more user data can be transmitted; however, the quality of channel quality feedback information will be lower, resulting in potentially inaccurate link adaptation decisions. The results from Monte Carlo computer simulation show that a global maximum for the throughput with respect to interval exists. The achievable throughput, however, strongly depends on the user mobility pattern.

Introduction: Link adaptation enables wireless transmitters to select the optimum combination of modulation and coding schemes (MCS) [1] based on prevalent radio channel conditions. Without link adaptation, a transmitter has to consider a worst-case channel quality in order to provide reliable communications. Link adaptation may be employed either by utilising blind channel estimation or by transmitting feedback information.

In this Letter, link adaptation based on feedback information for a time division multiple access (TDMA)-based single-carrier very high frequency (VHF) narrowband mobile ad-hoc network (MANET) is studied. For the link adaptation mechanism adaptive modulation and coding (AMC) is utilised where channel quality feedback (CQF) packets are transmitted from a recipient back to an originator. Since the MANET studied in this Letter targets applications where the bandwidth is strongly limited in order to enable large single-hop coverage (e.g. military communications or disaster search and rescue operations) minimisation of the signalling overhead is of major importance and is one of the most challenging issues to date. Our previous work [2] focusing on the characterisation of the link adaptation feedback has shown that the phenomenon of a constant CQF delay (e.g. due to queuing issues) of up to 10 cycles remains more a theoretical issue rather than a practical challenge. Hence, limited feedback remains beneficial for link adaptation.

System model: The system model is based on a single-carrier VHF narrowband MANET consisting of two node types: originators, which emit data packets and recipients receiving data packets. In this Letter, the random direction mobility model is applied. All the nodes move with a constant speed and get reflected at the frontiers of the simulation area. A constant bitrate multicast voice service capable of reaching a majority of the mobile recipients within a single hop is the primary service. The secondary service is a variable bitrate background data service. At the application layer, traffic is generated continuously at the maximum achievable data rate. For low data rates, at least the multicast voice service is transmitted. Whenever data rate is sufficient, the background data service will be transmitted in addition to the multicast voice service via piggybacking.

The present system model does not consider retransmissions at the link layer. Therefore, the calculated throughput is the net amount of data rate available for a transparent data service. The system uses TDMA with a superframe structure as per Fig. 1 to manage channel access. A superframe consists of $M+1$ frames whereby M depends on the feedback interval. Since the ability to establish either three quasi-parallel single-hop channels or at least one multi-hop (up to three hops) channel is required, each frame consists of three slots. The slot duration is designed to accommodate multicast voice packets even if the most robust MCS is applied. To avoid asynchrony between the application layer and the link layer, the TDMA frame duration is equal to the inter-departure rate of the multicast voice service as in the other voice-driven systems such as GSM. Only once within a superframe, i.e. in frame M, each slot is followed by a short control minislot (CS) to enable a transmission of the CQF as well as other control data. In frame M, a short CQF packet will be transmitted by the recipient for a data packet received of which at least the header has been received correctly. On receipt of the CQF, the originator is able to determine which MCS is appropriate for the next superframe period. Although the MCS for the data transmitted in regular slots is variable, the CQF is always transmitted using the most robust MCS.

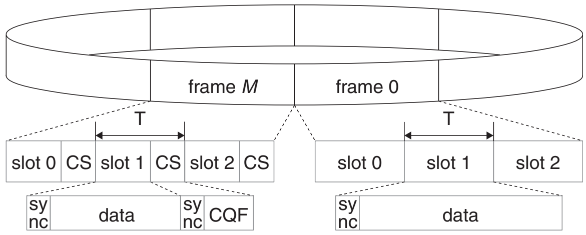

Fig. 1 *TDMA superframe structure consisting of $M+1$ frames. Frames 0 to $M-1$ accommodate data slots only, whereas frame M consists of both data slots and CS for CQF*

To select respective MCSs, a link adaptation algorithm based on signal-to-noise ratio (SNR) measurements is applied. Switching thresholds for the MCSs are selected in order to achieve a packet error rate (PER) of lower than or equal to 0.01, which is required for real-time applications such as voice services where the retransmissions cannot be applied. The MCSs considered in this Letter are presented in Table 1. It should be noted that the bitrate for each MCS represents the user net bitrate offered to the application layer for a frame consisting of data slots only. The physical layer is simulated in a detailed link level simulation where look-up tables are generated that associate the SNR with the PER. The link layer simulation is able to consider effects such as Doppler spread, multipath propagation, synchronisation, frequency offset, channel estimation and equalisation as well as filtering and oversampling aspects. 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 multipaths up to 100 µs may occur in the VHF band. The signals are affected by both a distance-dependent path loss [3] and fading due to shadowing. Shadowing is modelled as a zero-mean spatially correlated log-normal process [4] to consider the influences from buildings, hills etc. which are exploited by the link adaptation algorithm.

Table 1: MCSs utilised

IDs	MCSs	Bitrate (kbit/s)	IDs	MCSs	Bitrate (kbit/s)
0	BPSK 1/2	2.89	7	16-QAM 1/2	12.43
1	BPSK 2/3	3.94	8	16-QAM 2/3	16.65
2	BPSK 3/4	4.46	9	16-QAM 3/4	18.76
3	QPSK 1/2	6.09	10	16-QAM 5/6	20.87
4	QPSK 2/3	8.21	11	64-QAM 2/3	25.09
5	QPSK 3/4	9.26	12	64-QAM 3/4	28.26
6	QPSK 5/6	10.32	13	64-QAM 5/6	31.43

Numerical results: The most important parameters used in the Monte Carlo computer simulation are presented in Table 2. Hereby, several parameters relating to the radio channel and the physical layer have been taken from [3] as they are the results from the field measurements.

Table 2: Simulation parameters

Parameters	Settings	Parameters	Settings
Path loss exponent	4.25	System bandwidth	25.0 kHz
Reference distance	100 m	Noise figure	6 dB
Atten. at ref. distance	71.3 dB	Frame duration	180 ms
σ shadowing per link	5.12 dB	Slot/minislot dur.	{52, 60} ms/8 ms
Decorrelation distance	20 m	Inter-departure time	180 ms
Transmission power	0 dBm	Call duration	90 s
Carrier frequency	57.0 MHz	Simulation area	2200×2200 m

In the following, results are presented for the average user net throughput at the application layer considering both the multicast voice service and the background data service. Numerical values are normalised to the reference of 3 km/h and a feedback interval equal to one, i.e. to 8.57 kbit/s. Fig. 2 presents the normalised average user net throughput against the CQF interval for a link observed within a steady state. Therefore in this scenario, the MCS applied to the first packet is selected by assuming perfect knowledge about channel conditions. The abscissa represents the period in terms of the TDMA frames after which a CQF packet is transmitted by the recipient. Since the structure of the TDMA superframe provides the opportunity to establish three quasi-parallel single-hop data streams (compare Fig. 1), the originator emits its signals only in slot number 0. As the CQF interval increases, the average user net throughput increases too. By virtue of both the mobility model and the call duration selected, for a majority of the cases a velocity equal to 75 km/h achieves superior performance in terms of the normalised average user net throughput. However, for each value of the originator's speed, a global maximum exists. When the feedback interval is increased the maximum throughput drops.

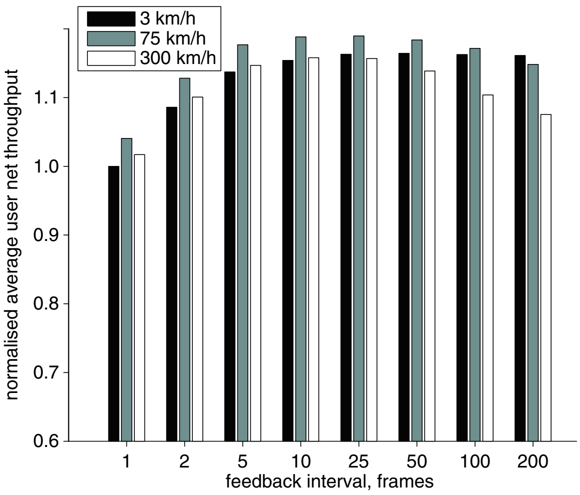

Fig. 2 *Normalised average user net throughput against CQF interval for link adaptation starting in steady state*

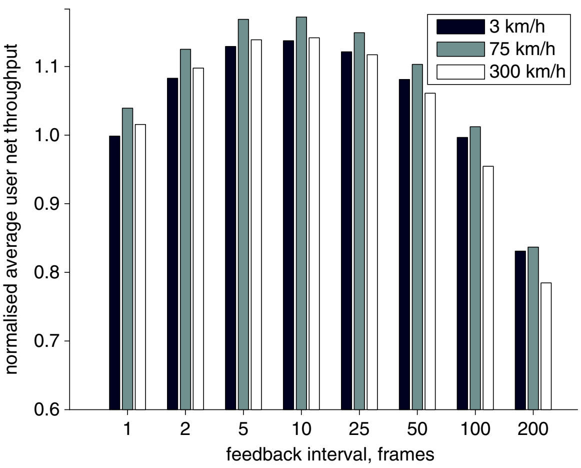

Fig. 3 *Normalised average user net throughput against CQF interval for link adaptation starting with basic MCS*

This behaviour can be explained as follows: increasing the CQF interval leads to a reduced accuracy in the MCS selection on the one hand, but also a reduction of the signalling overhead, and hence a reduction in the signalling overhead resulting in an additional user data rate on the other hand. However, as the inaccuracy exceeds a certain value, the probability that inappropriate MCSs are selected increases significantly, which in turn leads to an increasing probability of packet errors, and therefore a decreasing user net throughput. At this point, it should be noted that an increasing CQF interval also increases the probability that the current MCS is used for a longer period as the link adaptation algorithm is able to change the MCS if a CQF packet has been received or a timeout has occurred exclusively.

The graph in Fig. 3 shows the normalised average user net throughput against the CQF interval for a link which has just been initiated. Here, the most robust scheme, i.e. MCS 0, applies for the first packet to increase the call success probability, because for a new communication link no channel quality information is available. As is evident from Fig. 3, the qualitative behaviour is similar to the steady state. However, for the higher CQF intervals (i.e. ≥ 25), the average user net throughput is decreased more significantly. In fact, for a CQF interval of 200 frames, a reduction of about 30% can be observed compared with the steady state (compare Fig. 2). This degradation in an average user net throughput is not only the result of the effects as observed for the steady state but also due to the fact that initially the most robust MCS is applied. Therefore, the probability that a more robust MCS with a lower spectral efficiency applies for a longer period also increases which on the one hand improves the call success probability, but on the other hand clearly leads to a degradation in the throughput performance.

Conclusions: This Letter has studied the impact of the link adaptation feedback interval on the throughput in the TDMA-based narrowband VHF MANETs. It has been shown that in the case that AMC is employed for link adaptation a global optimum for the user net throughput may be achieved by adjusting the feedback interval, i.e. by trading accuracy of the CQF for a reduction in the signalling overhead. The optimum value for the feedback interval, however, strongly depends on the node's speed. For systems with the same design but different numerical parameter values, an identical qualitative behaviour may be expected. In time-limited voice communication, higher feedback intervals are tolerable without significant degradations. However, the throughput may be significantly improved in case the TDMA frame structure enables immediate transmission of a feedback for the first data packet. Hence, a more appropriate MCS may be applied to obtain a steady state. These insights may be beneficial specifically for the provisioning of single-carrier narrowband systems as the trade-off between the overhead and the system throughput is one of the most challenging issues. Moreover, the main findings are transferable to (wideband) multicarrier systems by assuming a finite number of narrowband subcarriers where the gain is scaled with the number of the subcarriers employed. Finally, in order to limit the system complexity, the number of MCSs supported by a real system is expected to be substantially lower.

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One or more of the Figures in this Letter are available in colour online.

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