Performance Comparison of Hierarchical Modulation Receiver Concepts for Different Service Classes

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***Abstract*—A narrowband transmission chain using conventional quadrature amplitude modulation (QAM) and soft-decoding is extended to implement hierarchical modulation. Packet error rate (PER) for different receiver concepts and modulation schemes is investigated using a multipath channel model. Two different data service classes are considered, a high priority (HP) voice stream and a low priority (LP) data stream striving for maximum throughput. Furthermore, the paper describes how hierarchical modulation is adjusted adaptively according to the channel conditions to increase the performance, i.e. the amount of successfully received data, in contrast to 4- and 16-QAM. The novel results show that hierarchical modulation achieves superior performance especially in the lower E_S/N_0 regions.**

Keywords*—Mobile ad-hoc networks, hierarchical systems, narrowband.

I. INTRODUCTION

Mobile ad-hoc networks (MANETs) have received significant attention particularly for search and rescue (SAR) applications and in security organisations where flexibility is required and only limited or no fixed infrastructure is available. MANETs in this application space mainly operate in the very high frequency (VHF) band to achieve long range communications but where bandwidth is scarce. These narrowband systems use bandwidths in the range of 25 to 50 kHz. Apart from the low data rates due to limited bandwidth, additional major challenges are harsh environments and mobility induced fast channel fluctuations.

Additional to voice communications, nodes have to transmit bulk data e.g. sensor information, position information, terrain maps, e-mail, or other bulk information [1]. Voice communication is typically a real-time application whereas data communication has less restrictive delay constraints and hence retransmissions can occur. The design of narrowband system which provide reliable voice communication with reasonable data rates is challenging and requires both flexible and adaptive mechanisms. One flexible approach to transmit services with different quality of service (QoS) classes is hierarchical modulation, also known as multi-resolution, embedded, asymmetrical, or nonuniform constellation, which is the focus of this paper.

II. RELATED WORK

Hierarchical modulation for Broadcast channels was introduced by Cover [2] in 1972. He showed that multi-resolution in character allows to exchange capacity between poor and good receivers for broadcast/multicast communication.

Hierarchical modulation is often mentioned in the context of multimedia communication and is well known as a part of the DVB-T and DVB-SH standard [3]. Most important television channels can be mapped onto the robust bits and additional television channels or HDTV [4] are mapped onto less protected bits. Receivers with good quality reception are able to receive both streams, whereby receivers with poor quality reception just receive the high priority (HP) stream.

In [5], Lim et al. investigate an independent decoding and a multi-stage decoding scheme for Gray and independent mapping in AWGN and Rayleigh channels. The decoding schemes contain demodulator, Viterbi decoders and interleavers without equalizer. A hierarchical modulation receiver with equalization based on a linear minimum mean square error (MMSE) algorithm is proposed by Zhang et al. in [6]. The decoder passes the extrinsic probabilities of the coded bits back to the equalizer as an iterative algorithm.

Based on the DVB-SH scheme, Zhe et al. [7] describe a 16-QAM-OFDM turbo code system for hierarchical modulation. The results show a gain in bit error performance by using Gray mapping. In [8], four demodulation algorithms with hard and soft-decisions for hierarchical modulation without Gray mapping are analytically compared. The proposed enhanced soft-decision based interference cancellation approach provides the best performance. The bit sequence of the HP stream is encoded, mapped and convoluted with the channel impulse response (CIR) to process the demodulation of the low priority (LP) stream.

A hierarchical M-QAM for different service classes and simultaneous voice transmission on the LP stream is numerically analysed over fading channels in [9]. In [10], two different services (voice and data) are transmitted by using an adaptive nonuniform PSK. Size and shape of the PSK constellation changes, according to the channel quality. This scheme is capable to maintain an error rate for the HP stream while transmitting additional data on the LP stream. An adaptive hierarchical scheme is also proposed in [11]. The ratios between the constellation distances are adjusted to maximize the transmission efficiency based on the channel conditions.

To the best of our knowledge, no previous work has considered a detailed single-carrier transmission chain in combination with soft-decoding and decision feedback equalizer including different bit mappings for hierarchical modulation. In this paper, a comprehensive study considering these receiver design concepts is presented and performance simulations with adaptive mechanisms are provided.

III. REFERENCE MODEL

In the following the reference model containing the single-carrier narrowband transmission chain and the very high frequency (VHF) multipath channel model is described.

A. *Narrowband physical layer transmission chain*

The reference model of the narrowband physical layer transmission chain for a uniform M-QAM, hereafter referred to as conventional modulation, is shown in Fig. 1.

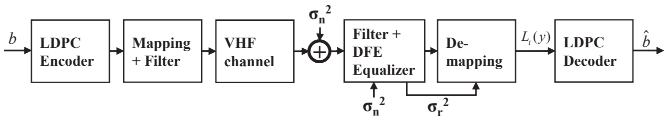


Fig. 1. Physical layer transmission chain for conventional modulation - b: information bit sequence, σ_n^2: noise variance, σ_r^2: estimated residual noise, $L_i(y)$: log-likelihood ratios, $\hat{b}$: received bit sequence.

The physical layer contains an irregular quasi-cyclic low-density parity-check (LDPC) encoder and decoder, as defined by IEEE 802.16e (WiMAX) [12]. Additionally, the transmission chain contains a M-QAM mapper and demapper, root raised cosine (RRC) filters for single carrier transmissions and a T/2-spaced finite-impulse-response (FIR)-minimum mean-square error (MMSE) decision-feedback equalizer (DFE). The decision feedback path of the equalizer requires hard decisions on the estimated soft symbols. The demapper calculates the approximate log-likelihood ratios (LLRs) using the residual noise (σ_r^2) estimated from the distances of hard-decision symbols and soft symbols. The demapper determines the LLR $L_i(y)$ for bit i given as max-log approximation [13]

$$L_i(y) = \frac{1}{\sigma_r^2}\left(\min_{a \in X_{i,0}}\left((y-a)^2\right) - \min_{a \in X_{i,1}}\left((y-a)^2\right)\right) \ , \quad (1)$$

where y is the soft symbol, a the ideal symbol of the set of symbols $X_{i,0}$ from the constellation diagram for the i^{th} bit with bit value 0 and $X_{i,1}$ the set of symbols with bit value 1.

B. *VHF Multipath Channel Model*

For our investigations a frequency-selective block fading channel model in the VHF band is considered. The CIR $h(\tau, t)$ is modelled as a wide sense stationary uncorrelated scattering (WSSUS) process given as

$$h(\tau, t) = \lim_{N \to \infty} \frac{1}{\sqrt{N}} \cdot \sum_{n=1}^{N} e^{j(\theta_n + 2\pi f_{D_n} t)} \cdot \delta(\tau - \tau_n) \ , \quad (2)$$

where each echo is characterized by a uniformly distributed phase θ_n $(0 \leq \theta_n < 2\pi)$, a delay τ_n $(0 \leq \tau_n \leq \tau_{max})$ and a Doppler shift f_{D_n} $(-f_{D_{max}} < f_{D_n} < f_{D_{max}})$ [14]. The delay is distributed exponentially and the Doppler frequency spread is according to Jakes spectrum.

IV. MAPPING AND RECEIVER CONCEPTS

The reference model in Fig. 1 is extended by a hierarchical modulation scheme. We consider two streams: One high priority (HP) voice stream requiring a certain packet error rate (PER) where retransmissions cannot be applied due to timing constraints and a low priority (LP) data stream with retransmissions striving for maximum throughput. The HP and LP streams are investigated separately in their performance for different receiver concepts assuming perfect estimation of CIR and noise variance σ_n^2. The numerical results are determined by Monte Carlo simulations in MATLAB.

A. *Mapping*

It is well known that the performance of a communication system is affected by the applied modulation scheme, which defines how payload bits are assigned to transmission symbols. Generally Gray coding is favourable for common M-QAM based transmissions.

1) Independent Mapping: Hierarchical modulation contains two or more streams simultaneously. Each stream can be modulated separately and combined into one physical signal. If each of these modulation schemes considers Gray mapping, the resulting constellation diagram has no Gray structure as adjacent symbols differ in more than one bit (see Fig. 2a). For instance, a 16-QAM can be achieved by the summation of two independent 4-QAM modulated signals. A hierarchical M-QAM signal $s(t)$ can be written as

$$s(t) = \sum_{k=1}^{k_{\text{stream}}} d_k s_k(t) \ , \quad (3)$$

where k denotes the index of the stream, d_k the scaling factor in (4) and $s_k(t)$ the modulated signal of stream k. The maximum number of streams is k_{stream}, in our case $k_{\text{stream}} = 2$.

The scaling factors d_1 and d_2 for a normalized mean power constellation are calculated as

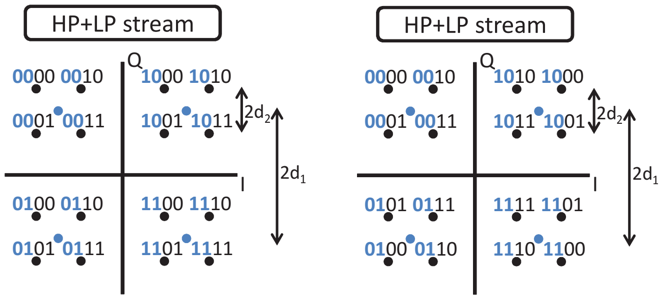
$$d_1 = \frac{1}{\sqrt{2(1+\beta^2)}} \text{ and } d_2 = \beta \frac{1}{\sqrt{2(1+\beta^2)}} \ , \quad (4)$$

where $\beta = \frac{d_2}{d_1}$ is the ratio of the scaling factors.

A normalized constellation diagram for a 16-QAM is achieved with $0 \leq \beta \leq 0.5$. Choosing $\beta = 0.5$ results in a regular signal space diagram with $d_1 = 2d_2$. With $\beta = 0$ the LP stream is deactivated and the resulting constellation diagram equals a 4-QAM ($d_2 = 0$).

The resulting constellation diagram for a hierarchical 16-QAM with two separate Gray coded 4-QAM streams is shown in Fig. 2a. The fictitious reference symbols of the HP stream (●) are centred between the LP reference symbols in each quadrant. These fictitious symbols are not actually transmitted. The actual transmitted set of reference symbols are represented with (●) for a 16-QAM.

2) Gray Mapping: In a Gray coded constellation diagram, adjacent symbols differ only in one single bit. The bits of the HP stream for the different symbols in each quadrant are equal. The symbols of the HP stream influence the mapping of the LP stream. Thus, mapping of the LP stream differs for each of the HP symbols. Additionally, the bits of the LP stream symbols do not differ from the adjacent symbols of another quadrant (symmetry of LP constellation with regards to I/Q-axis). In Fig. 2b, a Gray coded constellation diagram is shown for hierarchical 16-QAM modulation, similar to [3].



(a) Independent mapping (b) Gray mapping

Fig. 2. Mapping for hierarchical 16-QAM with (●) fictitious HP reference symbols and (●) 16-QAM reference symbols, $m = 4$, $\beta < 0.5$ and $d_1 > 2d_2$.

B. *HP Receiver*

First, receiver concepts for the HP stream are investigated.

1) HP Receiver Concepts: Based on (3) the hierarchical signal for HP and LP stream is separately encoded and modulated. The performance of the receiver is primarily influenced by the design of equalizer and demapper. The received signal can be interpreted as two separate signals which results in two different receiver approaches. The hard decision for the DFE path in the equalizer can be based on the resulting 16-QAM reference symbols or on the fictitious reference symbols of the HP stream (see Fig. 2a and 2b). The same variations also apply for the demapper where the LLRs rely on the distance between the estimated soft symbol and the reference symbols as shown in (1).

For the HP stream the following two receiver concepts are investigated:

- HP Approach 1: Equalizer and demapper are based on fictitious HP reference symbols.
- HP Approach 2: Equalizer and demapper consider the set of reference symbols of the resulting 16-QAM.

2) Numerical Results of HP Receiver Concepts: In Fig. 3, both HP receiver concepts for a hierarchical 16-QAM are compared with respect to PER for $\beta = 0.5$. Additionally, the performance of a conventional 4-QAM and a 16-QAM modulation scheme is depicted. The considered simulation parameters are listed in Table I. Since both, independent and Gray mapping, result in a Gray coded HP stream, the applied mapping scheme does not affect the PER of the HP stream. It can be seen from Fig. 3 that both hierarchical receiver concepts provide a lower performance compared to a conventional 4-QAM. The performance degradation is caused by the lower energy of the symbols which are close to the middle of the constellation diagram. In case of a hierarchical 16-QAM with $\beta = 0.5$, the inner symbols have a minimal Euclidean distance of $2d_2$ in contrast to a conventional 4-QAM having $2d_1$ where $d_1 > d_2$ for normalized constellation diagrams. The PER curve for Approach 1 reaches a floor at a PER of around 4%. The inferior performance can be explained by error propagation caused by the DFE path of the equalizer when deciding on the fictitious HP reference symbols. This also results in inaccurate calculation of the residual noise. Even for high E_S/N_0, the calculated residual noise still reaches a floor. Approach 2 provides better performance by considering the set of reference symbols of the resulting 16-QAM in equalizer and demapper. The approach is similar to the receiver with conventional modulation, except that the demapper only returns the LLRs of the HP bit stream. HP Approach 2 achieves an accurate estimation of the residual noise and the LLRs. It outperforms a conventional 16-QAM by about 4 dB and has also a performance degradation of around 4 dB compared to a QPSK at a PER of 10^{-2}. This HP receiver approach is considered in the following sections since it provides the best performance.

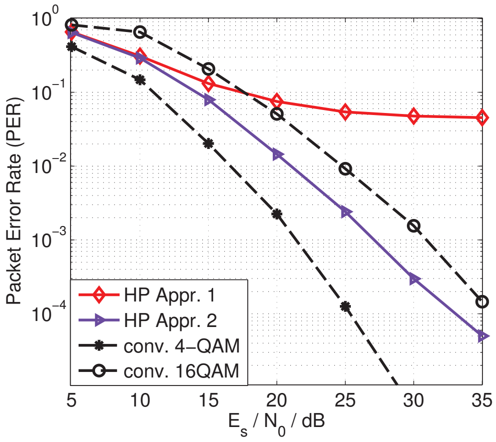


Fig. 3. Comparison of packet error rate (PER) for HP receiver concepts.

C. *LP Receiver*

In this section three different receiver concepts for the LP stream are discussed. For the sake of simplicity and readability the concepts are explained for a hierarchical 16-QAM containing two 4-QAM streams. Nevertheless, the concepts can also be applied to any other hierarchical modulation scheme.

1) LP Receiver Concepts:

- LP Approach 1 - Simple Demux:
  LP Approach 1 mainly relies on HP Approach 2, except that the demapper returns the LLRs for both, HP and LP stream (see Fig. 4). The LLRs are demuxed in HP and LP stream and independently decoded. This concept has the lowest complexity and smallest delay.

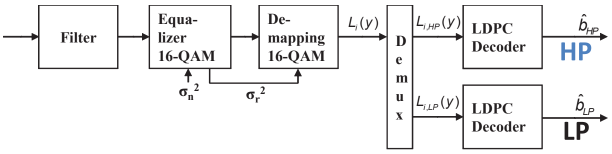


Fig. 4. LP Approach 1: Simple demux.

- LP Approach 2 - HP encoding and mapping:
  LP Approach 2 is a multi-stage decoder. The decoded HP bit-stream is encoded and mapped to subtract the

HP symbols from the equalized signal vector (see Fig. 5). The received symbols of the LP stream are gained in case of error-free decoding of the HP stream. The additional encoding, mapping and subtraction require accurate timing and increase the processing delay.

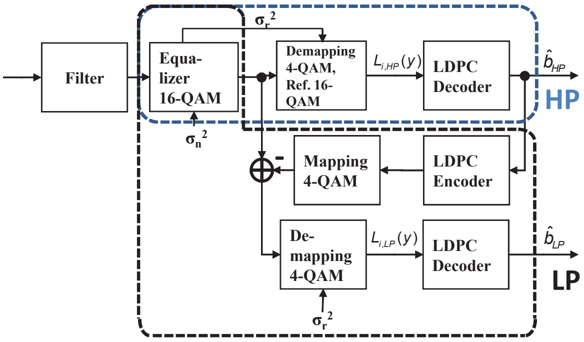


Fig. 5. LP Approach 2: HP encoding and mapping.

- LP Approach 3 - HP encoding, mapping, channel convolution and equalization:
  LP Approach 3 in Fig. 6 extends LP Approach 2 with the convolution of the mapped HP sequence with the CIR. The LP path contains an additional equalizer for downsampling from $T/2$- to T-spaced and for the calculation of σ_r^2 for the LP stream.

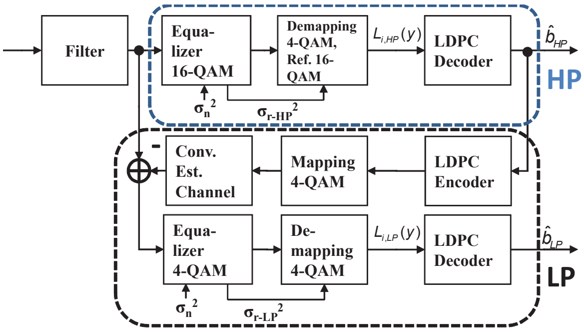


Fig. 6. LP Approach 3: HP encoding, mapping, channel convolution and equalization.

2) Numerical Results of LP Receiver Concepts: Fig. 7 shows the PER of the three LP approaches with independent (Ind.-M.) and Gray mapping (Gray-M.). In general, the expected decline in robustness for the LP stream compared to the HP stream is shown. The PER curve of Approach 1 is underneath the PER curve of Approach 2 for Gray mapping. For Approach 2 mapping shows no differences which can be explained by a reduction in faulty decisions on adjacent symbols by taking the decoded HP stream into account to determine the symbols for the LP stream. Gray mapping improves the performance by about 2 dB at PER = 10^{-2} compared to independent mapping for Approach 1. The bits of the LP stream in Gray mapping are symmetric around the I and Q axes resulting in higher robustness to bit errors. Approach 3 contains a convolution with the CIR and an additional equalizer for the LP stream. The results show that the performance of Approach 3 is nearly independent of the mapping. The performance is improved by more than 2 dB compared to Approach 1 and 2. In contrast to Approach 2, Approach 3 separates the error propagation in the equalizer in HP and LP stream. The decoded symbols of the HP stream are encoded again, mapped and convoluted with the CIR. Subtracting this signal from the received signal extracts the LP modulated signal which can be equalized, demapped, and decoded. This layered approach outperforms the conventional 16-QAM by mitigating the impact of error propagation. For conventional 16-QAM, error propagation impacts the whole packet. For Approach 3, error propagation in the DFE of the HP stream can be corrected by the LDPC before the LP stream is separately equalized. However, this approach introduces an additional delay between HP and LP stream due to the decoding and equalization. In conclusion, LP Approach 3 achieves the best performance but has also the highest complexity. The two different mappings, independent and Gray, provides no appreciable performance differences for LP Approach 3. From this point forth in the paper, investigations consider only LP Approach 3 with Gray mapping as it yields the best performance results.

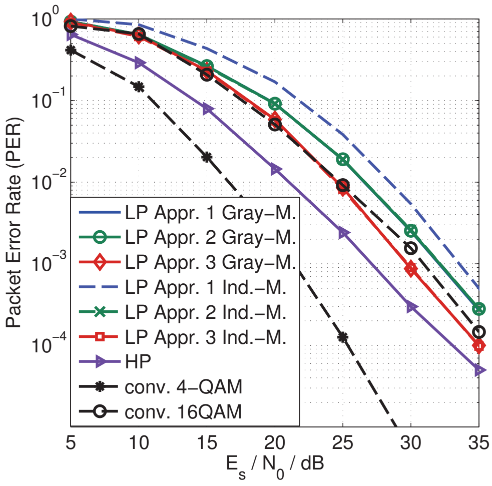


Fig. 7. Comparison of packet error rate (PER) for LP receiver concepts.

TABLE I. SIMULATION PARAMETERS.

Parameter name	Value
Symbol duration (T)	50 μs
RMS delay spread (σ_{T_m})	14.5 μs
Maximum LDPC iterations ($I_{\max}$)	30
Code rate (R)	1/2
Information symbols per packet	492 symbols

V. ADAPTIVE HIERARCHICAL SCHEME AND GOODPUT CONSIDERATION

Two service classes are considered. The first service class is a constant bit rate service requiring a target PER $\leq 10^{-1}$ for e.g. robust voice transmission. Since voice is a real-time application which is delay restricted, no retransmissions are applied. This service class is mapped on the HP stream in case of hierarchical modulation. Adapting β allows to satisfy the target PER for the HP stream by trading off the robustness between HP and LP. With $\beta < 0.5$, d_2 decreases whereby d_1 increases. The step-width of β in (4) is 0.05. The second service class is not delay restricted and is transmitted in addition to the voice stream with hierarchical modulation. For the LP stream selective repeat automatic repeat request (SR-

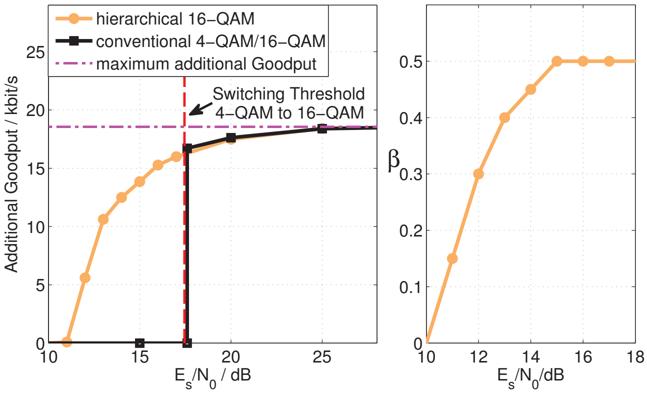


Fig. 8. Comparison of additional goodput and adaptive β for a target PER $\leq 10^{-1}$ on the HP stream for a multipath channel.

ARQ) is applied. The feedback is assumed to work perfectly, which means error-free and without requiring any resources i.e. time on air. Both streams are simultaneously transmitted using a hierarchical 16-QAM scheme, i.e. 4-QAM is used on both streams with code rate R=1/2. Since the second stream has lower priority and is optionally transmitted, we define the "additional goodput" as the amount of successfully received data in a time period on the LP stream.

A. Adaptive β

In the constellation diagram β is adjusted to constantly satisfy a PER $\leq 10^{-1}$ for the HP stream, illustrated in Fig. 8.

B. Additional Goodput at the LP Stream with SR-ARQ

The additional goodput in Fig. 8 is determined numerically based on the simulated PER of the LP stream with adaptive β and compared to a conventional 4-QAM and 16-QAM. The results show that the conventional 16-QAM can be used for an $E_S/N_0 >$ 17.5 dB to satisfy the requirement on PER $\leq 10^{-1}$. At lower E_S/N_0 a conventional 4-QAM can be applied to transmit the first service class without additional goodput. In contrast, hierarchical modulation is able to transmit additional data already at lower signal quality. By increasing β the LP stream becomes more robust at the expense of the robustness of the HP stream. The additional goodput with 16-QAM is nearly similar to hierarchical modulation for $E_S/N_0 >$ 17.5 dB. In general, hierarchical modulation achieves an increase in goodput specifically for multiple classes of services. In our simulation an additional goodput is achieved for E_S/N_0 in the range of 11 to 17.5 dB. However, it should be noted that another approach to increase the goodput for both, conventional and hierarchical modulation, is to adapt the code rate.

VI. CONCLUSION

A narrowband transmission chain has been extended by hierarchical modulation. Two receiver concepts for high priority (HP) voice stream transmission and three concepts for low priority (LP) data stream transmission have been compared with different bit mapping approaches considering perfect estimation of channel impulse response (CIR) and noise variance. The best PER for the HP stream is achieved by utilizing the set of reference symbols of the resulting M-QAM (e.g. 16-QAM) in equalizer and demapper. To obtain the best performance for the LP stream it is necessary to encode, map and convolute the received decoded HP bit stream with the CIR to achieve an accurate subtraction of the HP stream from the received symbols. Depending on the receiver approach, Gray mapping outperforms or equals the performance of independent mapping. Furthermore, simultaneous voice and data transmission has been considered. By adapting the ratios between the constellation distances, the HP stream satisfies the target PER $\leq 10^{-1}$. Hierarchical modulation achieves additional goodput compared to conventional 4-QAM and 16-QAM schemes especially in the lower E_S/N_0 region but has higher complexity and causes larger delay.

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