Relay Communication with Hierarchical Modulation

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***Abstract*— We consider a relay communication with distributed channel coding. The source broadcasts channel encoded and modulated information to the relay and to the destination. In a second time slot, the relay sends additional redundancy to the destination. The broadcast from the source leads to the dilemma of adjusting the modulation scheme to the relay or to the destination link. We propose to use hierarchical modulation to solve this dilemma. We show with simulation results that the proposed system achieves a significant gain compared to reference systems.**

***Index Terms*— Relay channel, hierarchical modulation, broadcast, channel coding.**

I. Introduction

THE application of relays in cellular based wireless communication systems is in discussion to increase the spectral efficiency. If we use relays in a simple form for the uplink, the mobile station sends its encoded data in a first time slot to the relay, which can be installed for example on a traffic light. The relay decodes and reencodes the data and then forwards it in a second time slot to the base station. Although two transmissions are necessary, the relay communication can outperform the point-to-point communication because the mobile station-relay and the relay-base station link have to overcome a smaller distance and provide a higher signal-to-noise ratio (SNR) than the mobile station-base station link. The higher SNR allows to use higher modulation schemes than for the point-to-point communication. For example, if each modulation symbol can carry 6 code bits for the relay communication and only 2 code bits for the point-to-point communication and the channel encoder outputs 2 code bits per information bit (code rate 0.5), the spectral efficiency of the relay communication is $(0.5 \cdot 6)/2 = 1.5$ information bits per channel use compared to the point-to-point communication with $0.5 \cdot 2 = 1$ information bit per channel use.

The wireless broadcast nature allows the base station to listen to the transmission of the mobile station as well. We can use coded cooperation [1] with distributed channel coding for such a system. Then, the base station listens to the transmission from the mobile station in the first time slot and obtains additional redundancy from the relay in the second time slot. This provides a better error protection. Moreover, distributed channel coding allows to gain cooperative diversity [2], [3] in a fading environment.

Typically, the SNR of the mobile station-base station link is smaller than the SNR of the mobile station-relay link and thus, a modulation scheme with lower order would be suitable for the mobile station-base station link than for the link to the relay. The broadcast from the mobile station leads to the dilemma whether to adjust the order of the modulation scheme according to the SNR to the relay or according to the SNR to the base station. If we adjust the modulation order according to the SNR to the base station and use a low modulation scheme, then we cannot improve the throughput as it is described in the previous example. If we adjust the modulation order according to the SNR to the relay and choose a high modulation scheme, the base station cannot demodulate the received signal reliable and thus, the advantages of distributed channel coding cannot be exploited.

A solution for this dilemma is the use of hierarchical modulation which is included in the digital video broadcast (DVB) standard [4]. Hierarchical modulation allows to use a modulation scheme which can be interpreted as a scheme with higher order by the receivers close to the transmitter and as a scheme with lower order by the receivers far from the transmitter. The advantage of broadcast strategies, like hierarchical modulation, was first shown in information theory in [5]. The design for a real system applying such broadcast strategies was first described in [6]. The use of such broadcast strategies for the relay channel was investigated information-theoretically in [7]. To the best of our knowledge, no real system design with broadcast strategies for the relay channel has been proposed.

In this letter, we describe how the application of hierarchical modulation can be realized in a relay communication system with distributed turbo codes [8]. Simulation results for additive white Gaussian noise (AWGN) channels show that the application of hierarchical modulation can achieve a gain in term of bit and packet error rates.

II. System Description

We consider the uplink in a cellular based mobile communication system. A block diagram of the system is depicted in Fig. 1.

The mobile station MS wants to transmit data which is segmented in packets $\mathbf{u}$ of $K = 1500$ bits to the base station BS. The information bits $\mathbf{u}$ are protected against transmission errors with a channel encoder (chan. enc.). We choose the turbo code of the universal mobile telecommunication system (UMTS) standard [9] with two parallel concatenated recursive 8-state rate-1/2 convolutional codes as channel encoder, which outputs the block of code bits $\mathbf{c}$ with length $N = 4512$, including twelve tail bits. We include a cyclic redundancy check (CRC) as error detection code. The puncturing block chooses from $\mathbf{c}$ two subsets $\mathbf{c}_\mathrm{C}$ and $\mathbf{c}_\mathrm{E}$, each with 1500 bits. The block $\mathbf{c}_\mathrm{C}$ contains the common bits which are supposed to

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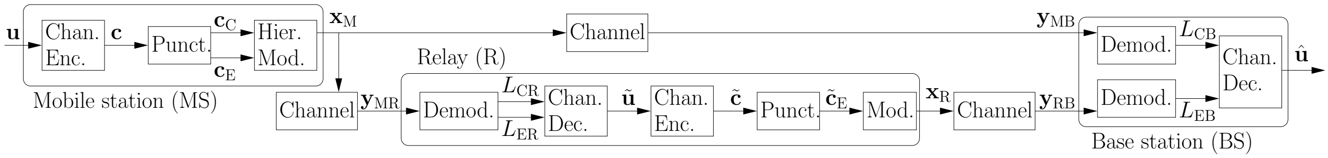

Fig. 1. Block diagram of the communication from the mobile station to the base station with the help of a relay. The mobile station uses hierarchical modulation (hier. mod.) for the broadcast to the relay and to the base station.

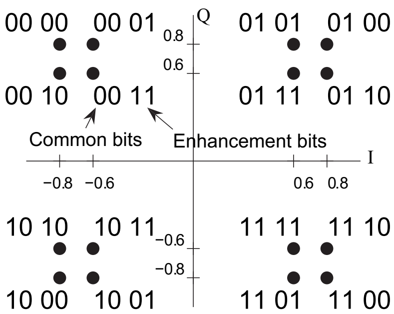

Fig. 2. Mapping for the hierarchical modulation at the mobile station. The common bits in $\mathbf{c}_{\text{C}}$ are better protected than the enhancement bits in $\mathbf{c}_{\text{E}}$.

be detected in the first time slot at both the relay and the base station. The block $\mathbf{c}_{\text{E}}$ contains the enhancement bits which are supposed to be detected in the first time slot only at the relay. We choose the systematic bits as common bits $\mathbf{c}_{\text{C}} = \mathbf{u}$. The enhancement bits in $\mathbf{c}_{\text{E}}$ include every second redundancy bit[1] from each stream of the two parallel concatenated encoders within the turbo encoder. The hierarchical modulation (hier. mod.) maps 2 bits from $\mathbf{c}_{\text{C}}$ and 2 bits from $\mathbf{c}_{\text{E}}$ to one symbol according to the inphase/quadrature (I/Q) constellation depicted in Fig. 2.

As symbols at minimum Euclidean distance differ in one bit, it is a Gray mapping. The first two bits are from $\mathbf{c}_{\text{C}}$, the other two bits are from $\mathbf{c}_{\text{E}}$. The constellation can be interpreted as a superposition of the enhancement and the common bits where $\alpha = (0.1 \cdot \sqrt{2})^2 = 2\%$ and $1 - \alpha = (0.7 \cdot \sqrt{2})^2 = 98\%$ of the transmitted power are allocated to the enhancement and the common bits, respectively. This assures that the common bits are much better protected than in a conventional, equidistant constellation. An optimization of the power allocation could be done in further work. The mobile station transmits the block $\mathbf{x}_{\text{M}}$ which contains $M_{\text{M}} = 750$ symbols in the first time slot.

The demodulation at the relay receives in the first time slot the disturbed symbols from the mobile station $\mathbf{y}_{\text{MR}}$ and outputs log-likelihood ratios (LLRs) $L_{\text{CR}} = L(\mathbf{c}_{\text{C}}|\mathbf{y}_{\text{MR}})$ and $L_{\text{ER}} = L(\mathbf{c}_{\text{E}}|\mathbf{y}_{\text{MR}})$ about both the common and the enhancement bits. Based on $L(\mathbf{c}_{\text{C}}|\mathbf{y}_{\text{MR}})$ and $L(\mathbf{c}_{\text{E}}|\mathbf{y}_{\text{MR}})$, the channel decoder outputs an hard estimate $\tilde{\mathbf{u}}$ about $\mathbf{u}$. The decoder for the turbo code uses five iterations. If the CRC indicates that the relay decoded successfully, the estimate $\tilde{\mathbf{u}}$ is encoded with the same turbo code as at the mobile station to the block $\tilde{\mathbf{c}}$. The puncturing block chooses from $\tilde{\mathbf{c}}$ the previously used subset $\tilde{\mathbf{c}}_{\text{E}}$ of 1500 bits, which are mapped to 16-Quadrature-Amplitude-Modulation (16-QAM) symbols. The block $\mathbf{x}_{\text{R}}$ of $M_{\text{R}} = 375$ symbols is sent to the base station in the second time slot. If the CRC indicates non-successful decoding, the relay notifies the mobile station, using one bit in a control channel, to transmit 375 4-QAM symbols containing every second redundancy bit from $\mathbf{c}_{\text{E}}$ in the second time slot. The second time slot contains half the number of symbols compared to the first one.

The base station receives in the first time slot the disturbed symbols from the mobile station $\mathbf{y}_{\text{MB}}$. The demodulation treats $\mathbf{y}_{\text{MB}}$ as a block of 4-QAM symbols and only outputs LLRs $L_{\text{CB}} = L(\mathbf{c}_{\text{C}}|\mathbf{y}_{\text{MB}})$ about the common bits[2]. In the second time slot, the base station receives either the disturbed symbols from the relay $\mathbf{y}_{\text{RB}}$ which are demodulated to the LLRs $L_{\text{EB}} = L(\mathbf{c}_{\text{E}}|\mathbf{y}_{\text{RB}})$ about the enhancement bits or more symbols from the mobile station which can be also demodulated to LLRs about the enhancement bits. The turbo decoder at the base station uses both the LLRs about the common and about the enhancement bits to output the estimate $\hat{\mathbf{u}}$ after five iterations.

The channel from the mobile station to the relay is described by $\mathbf{y}_{\text{MR}} = a_{\text{MR}} \cdot \mathbf{x}_{\text{M}} + \mathbf{n}_{\text{MR}}$, the channel from the mobile station to the base station by $\mathbf{y}_{\text{MB}} = a_{\text{MB}} \cdot \mathbf{x}_{\text{M}} + \mathbf{n}_{\text{MB}}$ and the channel from the relay to the base station by $\mathbf{y}_{\text{RB}} = a_{\text{RB}} \cdot \mathbf{x}_{\text{R}} + \mathbf{n}_{\text{RB}}$, where a_{MR}, a_{MB} and a_{RB} depict the path-loss and the elements of $\mathbf{n}_{\text{MR}}$, $\mathbf{n}_{\text{MB}}$ and $\mathbf{n}_{\text{RB}}$ are complex zero-mean Gaussian noise with variance $\sigma^2 = N_0/2$ in each real dimension. The mobile station and the relay use the same transmission power P. The SNR on the MS-BS link is given by $E_{\text{S}}/N_0 = (a_{\text{MB}}^2 \cdot P)/(2 \cdot \sigma^2)$. We assume a path-loss exponent of 3.52 and that the relay is at half distance between mobile and base station. Then, the SNR in dB on the MS-R and the R-BS link is given by $E_{\text{S}}/N_0|_{\text{dB}} + 35.2 \cdot \log_{10}(2)$ dB $= E_{\text{S}}/N_0|_{\text{dB}} + 10.6$ dB.

III. Reference Systems

A. Relay Communication without Hierarchical Modulation

The first reference systems uses no hierarchical modulation. If the mobile station sends $M_{\text{M}} = 750$ 16-QAM symbols, the base station demodulates both the code bits in $\mathbf{c}_{\text{C}}$ and in $\mathbf{c}_{\text{E}}$. As the base station already receives the code bits in $\mathbf{c}_{\text{E}}$ from the mobile station, the relay sends $M_{\text{R}} = 375$ 16-QAM symbols which contain other 1500 code bits from $\tilde{\mathbf{c}}$ which were not sent by the mobile station. Although the base station receives 1500 code bits more than in the system with hierarchical modulation, we expect this system to be worse because the base station can demodulate the code bits in $\mathbf{c}_{\text{C}}$ more efficiently, if hierarchical modulation is used.

[1] As we want to include also every second of the twelve tail bits, we omit six other redundancy bits.

[2] The demodulator could output additional LLRs about the enhancement bits. However, this requires a higher demodulation complexity and the resulting benefit is only 0.03 dB in the simulation described in Section IV.

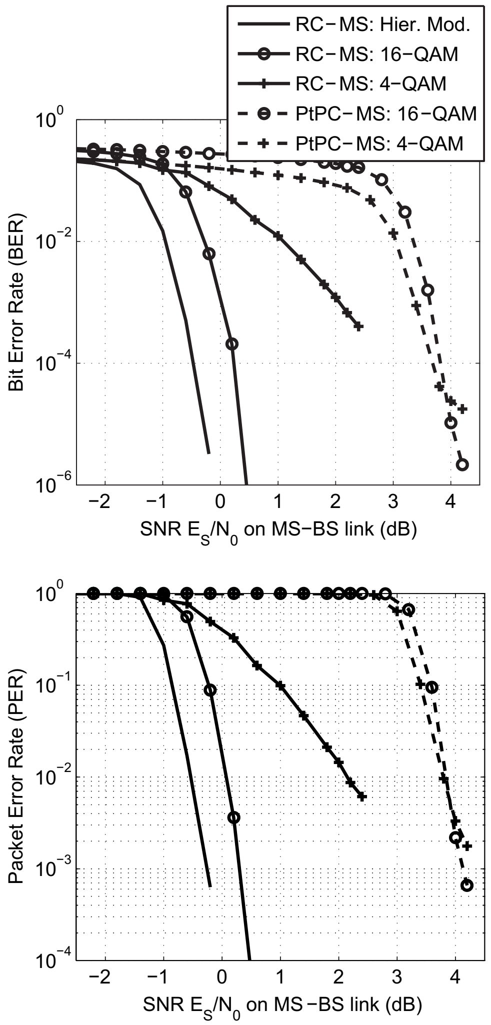

Fig. 3. Bit error and packet error rate for the relay channel (RC) with the proposed hierarchical modulation (hier. mod.), 4-QAM or 16-QAM at the mobile station (MS). All systems use 16-QAM at the relay. The error rates for the point-to-point channel (PtPC) are depicted with 4-QAM and 16-QAM.

If the mobile station broadcasts $M_{\mathrm{M}} = 750$ 4-QAM symbols containing the code bits in $\mathbf{c}_{\mathrm{C}}$, we expect the performance to be worse, because then, the relay cannot use any redundancy for error protection. If the relay decodes successfully nevertheless, it sends 375 16-QAM symbols containing the code bits in $\mathbf{c}_{\mathrm{E}}$. Otherwise, the mobile station sends 375 4-QAM symbols containing every second bit from $\mathbf{c}_{\mathrm{E}}$ in the second time slot.

B. Point-to-Point Communication

The second reference system describes a point-to-point communication with the previous mentioned turbo code. The mobile station sends 750 symbols in the first time slot and 375 symbols in the second time slot. We use either 4-QAM or 16-QAM symbols at the mobile station.

IV. Simulation Results

We compare the bit error rate (BER) and packet error rate (PER) between $\mathbf{u}$ and the estimate $\hat{\mathbf{u}}$ at the base station with a Monte Carlo simulation of the relay communication system with hierarchical modulation and of the two reference systems described in Section III.

Fig. 3 depicts the BER and PER over the SNR on the MS-BS link. The dashed lines depict the error rates of the point-to-point communication with either 16-QAM or with 4-QAM. The relay communication without hierarchical modulation with 16-QAM at the mobile station gains more than 3.5 dB at a PER of 10^{-2} compared to the point-to-point communication. The relay communication without hierarchical modulation with 4-QAM suffers from a high error rate at the relay, which cannot use any redundancy to recover the data, and thus, this system looses around 2 dB at a PER of 10^{-2} compared to the relay system with 16-QAM at the mobile station.

The proposed relay communication with hierarchical modulation outperforms the reference systems and gains around 0.6 dB at a PER of 10^{-2} to the best reference system.

V. Conclusion

We described how to improve a relay communication with distributed turbo coding by using hierarchical modulation at the source. This allows that the modulation for the broadcast from the source can be adjusted both to the link to the relay and to the destination, even if both links have a different channel quality. Simulation results for our examples with AWGN channels showed that the system with hierarchical modulation can outperform the reference systems by 0.6 dB.

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