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Adaptive modulation for completion time minimization in wireless broadcast networks ☆

Melda Yuksel *, Yasin Genç

Electrical and Electronics Engineering Department, TOBB University of Economics and Technology, Sogutozu, Ankara 06560, Turkey

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A B S T R A C T

In this work we study the effect of hierarchical modulation on completion time minimization in wireless broadcast channels. Time needed to transmit all bits intended for a particular user is defined as its completion time. In this work we investigate minimizing the maximum completion time over all users in a broadcast channel using hierarchical modulation. We compare time division, opportunistic scheduling, and three different adaptive modulation schemes: rate adaptive hierarchical modulation assisted transmission (HA), modified HA (MHA) and optimal HA (OHA). While HA aims at maximizing total throughput, OHA minimizes the maximum completion time, and MHA provides an intermediate solution. It is observed that OHA always chooses the best superposition order and the constellation size to minimize the maximum completion time.

1. Introduction

In a two-user broadcast channel, there is one source and two destination nodes. The source node has two distinct messages for each one of the destinations. This channel was introduced in [1] and superposition coding was suggested as an achievability scheme. It was shown in [2] that superposition coding is optimal for the degraded broadcast channel.

The practical way to implement superposition coding in digital broadcast systems is via hierarchical modulation with multistage decoding [3–6]. A two-level hierarchical signal constellation can be thought of as a superposition of two different signal constellations with different minimum distances. Signal points are non-uniformly placed, and base and enhancement layer bits in a symbol are protected at different levels. Hierarchical modulation has many application areas such as in relay channels [7–9] and scalable video broadcast [10,11].

In a point-to-point channel, when channel state information is available at the transmitter, modulation, coding and transmission power can be adapted to channel conditions for enhanced throughput and spectral efficiency [12]. For example, in [13], a turbo trellis coded modulation is designed that performs very close to the capacity region of a given degraded broadcast channel. In general, time-varying wireless channels have continuous probability density functions, and capacity achieving joint modulation and coding design for each channel gain pair is not feasible. Instead, for a fixed coding scheme, modulation schemes can be adapted to channel conditions. In [14,15], a rate adaptive hierarchical modulation-assisted two-user opportunistic scheduling scheme is proposed for enhanced total spectral efficiency. In this scheme, whenever channel conditions can accommodate two users; i.e. satisfying individual bit error rate requirements, hierarchical modulation is used for simultaneous transmission. Otherwise, single user transmission is continued. Power control for scheduling with hierarchical modulation is studied in [16]. It is also shown in [17] that via the two-best user scheduling scheme of [14], in a wireless network buffers are less occupied and channel access delay is lower. Hierarchical constellations can also lower transmission delays and can accommodate different priority level packets simultaneously, increasing the overall throughput [18].

The above mentioned studies focus on maximizing total throughput. In [19], authors take a different approach, and reconsider adaptive modulation for network utility maximization for multiple flow single-link and multiple interfering links. In this work, we seek for an adaptive hierarchical modulation scheme that minimizes the maximum completion time in a two-user broadcast channel. Completion time is defined as the time that is spent from the generation of a packet till its successful reception [20,21]. The completion time metric is of interest when delay-sensitive information, such as real-time video, is being transmitted. In such systems, each user wishes to receive its own information as soon

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* Corresponding author.
E-mail address: yuksel@etu.edu.tr (M. Yuksel).

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as possible. Moreover, some loss in throughput can be tolerated as long as the requested information arrives in a timely manner.

In multiuser settings, maximizing throughput is not equivalent to minimizing completion time. For example, in a two-user broadcast channel, for maximum sum throughput, communication must take place only with the user with better channel conditions. With this approach the worse user always has to wait for the better user and this is clearly suboptimal in terms of completion time. In this work, we compare the maximum completion time performances of time division (TD), opportunistic scheduling (OS), and rate adaptive hierarchical modulation assisted transmission (HA) [14] with the newly proposed modified HA (MHA) and optimal HA (OHA). While HA aims at maximizing total throughput, OHA is the solution of the smallest completion time problem. The MHA scheme is shown to perform in between HA and OHA. Depending on how fast channel conditions change, OHA introduces significant gains with respect to HA and MHA.

Next, we introduce the system model in Section 2 and state the transmission protocols in Section 3. We present the numerical results in Section 4, and finally conclude in Section 5.

2. System model

In this work, we study a block fading broadcast channel with two receivers. The input-output relations are given as

$$Y_{1,b,i} = h_{1,b}X_{b,i} + Z_{1,b,i} \tag{1}$$

$$Y_{2,b,i} = h_{2,b}X_{b,i} + Z_{2,b,i}, \tag{2}$$

where b is the block index $b = 1, 2, \ldots$, and i is the symbol index within block $b, i = 1, \ldots, n$. Here $X_{b,i}$ denotes the signal the source transmits, and $Y_{l,b,i}$ and $Z_{l,b,i}$ respectively denote the received signal and the noise at node $l, l = 1, 2$, in block b at symbol index i. We assume $Z_{l,b,i}$ are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance N_0. Each block lasts for n channel uses, i.e. the channel remains fixed for $i = 1, \ldots, n$, and changes independently from one block to the other. The channel gains, $h_{l,b}$ are assumed to be i.i.d. complex Gaussian with zero mean and unit variance. Channel state information is available both at the source and the receivers. The average symbol energy at the source is $\mathscr{E}$. The received signal to noise ratio (SNR) values at the destinations are respectively denoted with $\gamma_{1,b}$ and $\gamma_{2,b}$, where $\gamma_{l,b} = |h_{l,b}|^2\mathscr{E}/N_0$. The source node has two packets of length L_1 and L_2, respectively destined to the first and the second receivers. There are fixed target bit error rate constraints at each of the receivers, respectively equal to p_1 and p_2.

We consider simultaneous transmission to both users via hierarchical modulation. A symbol $X_{b,i}$ is composed of base and enhancement layer bits, each layer destined to one of the receivers. In N/M QAM, $\log_2 N$ and $\log_2(M \div N)$ bits are respectively transmitted to the base and enhancement layer users. The base layer user only decodes its own bits, while the user served in the enhancement layer decodes both base and enhancement layers, although its information is only in the enhancement layer.

We assume the channel coherence time is long, i.e. n is large and when transmission to the two users take place simultaneously, both users' packets are delivered within the coherence time. However, due to differences in packet lengths, reliability constraints and transmission rates, both receivers do not necessarily finish receiving their packets at the same time or even simultaneous transmission is not possible. Thus, we investigate two cases:

Case (i): Scheduling decisions and the modulation scheme to be used are determined at the beginning of each block and remain fixed until the next block.

Case (ii): Scheduling decisions and the corresponding modulation scheme can change within a block.

We elaborate on the details of these cases in Section 3, when we introduce the transmission schemes.

In the next section, we introduce the protocols time division (TD), opportunistic scheduling (OS), hierarchical modulation assisted transmission (HA), modified HA (MHA), and the optimal HA (OHA). Let $T_{C1,m}$ and $T_{C2,m}$ denote the completion times for each one of the receivers for protocol $m, m = \{\text{TD, OS, HA, MHA, OHA}\}$. Then the completion time for protocol m is defined as the maximum of the individual values, $T_{C,m} = \max\{T_{C1}, T_{C2}\}$, measured in terms of the number of symbol intervals. In Section 4, we compare these transmission schemes in terms of their achievable $T_{C,m}$ for both cases (i) and (ii).

3. Transmission schemes

In this section TD, OS, HA, MHA and OHA transmission protocols are explained in detail.

3.1. Time division (TD)

In TD, the users are served in tandem. We consider M-ary quadrature amplitude modulation (QAM) signal constellations, where $M = 4, 16, 64$ or 256. The exact bit error rate expressions for uniform square QAM constellations are given in [22]. Using these expressions, we find the received SNR threshold value $\mathbf{g}_M$, for which the exact bit error rate for M-QAM equals p_l, the target bit error rate of user l. Then, in TD, when a user $l, l = 1, 2$, is to be served, the source node chooses the largest modulation scheme, which satisfies user l's reliability constraint p_l. In other words, it seeks for the largest M for which $\gamma_{l,b} \geqslant \mathbf{g}_M$ for M-QAM to be feasible. If the channel condition is too poor to support even 4-QAM, then the source node waits for n channel uses for the channel to change.

In TD, we assume that user 1 is always scheduled the first. The source node transmits to user 1 with the largest feasible modulation scheme that satisfies the bit error rate constraint p_1. If no such constellation is present, transmission is delayed until the next block. Suppose for the first $B-1$ blocks, $\gamma_{1,b} < \mathbf{g}_4$, and user 1 is able to transmit its packet in block B, which lasts for I symbols. Then for case (i), there is no transmission for the remaining $n - I$ symbols in block B. The second user can start its transmission in block $B+1$, if $\gamma_{2,B+1} > \mathbf{g}_4$. Suppose the second user waits for β blocks for a favorable channel and its transmission last ζ symbols. Then $T^{(i)}_{C,TD} = \max\{(B-1)n + I, Bn + \beta n + \zeta\}$. Otherwise, it waits until a favorable channel condition occurs. In case (ii), transmission to the second user can immediately start in block B, at symbol index $I+1$ if $\gamma_{2,B} > \mathbf{g}_4$. Then $T^{(ii)}_{C,TD} = \max\{(B-1)n + I, (B-1)n + I + \zeta\}$. If the second user cannot start its transmission in block B and waits β more blocks, $T^{(ii)}_{C,TD} = \max\{(B-1)n + I, Bn + \beta n + \zeta\}$.

As the above example shows, case (i) is reminiscent of a slotted ALOHA scheduling policy. Case (ii), on the other hand, allows for a user to be scheduled immediately after the previous one ends, i.e. within the same block. This refers to a more complex scheduling scheme, which requires better synchronization and coordination in a wireless network.

3.2. Opportunistic scheduling (OS)

The OS protocol is the same as TD except the user with the larger channel gain is served the first. As the user served the second waits for the first, it is meaningful to schedule the user with smal-