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Feedback Constraints for Adaptive Transmission

Limits of AMC and MIMO for frequency division duplex systems

The growth of wireless networks in recent years coupled with applications demanding high data rates underscores the fact that the communication system is bandwidth- and power-limited. Therefore, an efficient utilization of the radio spectrum is of paramount importance, particularly in developing bandwidth- and power-efficient communication systems. Adaptive transmission has emerged as a viable approach to boost transmission rates in a communication system. Adaptive transmission refers to signaling strategies that adapt some combination of the modulation, transmit power, and coding scheme in response to channel variations. This is rather different from the traditional design methodology, where a transmission power margin is provided to ensure reliable communication in the event of a deep fade. The significant spectral efficiency gains provided by adaptive modulation and coding (AMC) has resulted in its adoption in current and proposed wireless standards including the wideband code division multiple access (WCDMA) high-speed downlink packet access

(HSDPA) [1], CDMA2000, third generation (3G) long-term evolution [2], IEEE 802.11 wireless local area network (WLAN), and IEEE 802.16 broadband wireless access standards.

ADAPTIVE TRANSMISSION HAS EMERGED AS A CANDIDATE TECHNOLOGY FOR BANDWITH -AND POWER-EFFICIENT HIGH SPEED COMMUNICATION SYSTEMS.

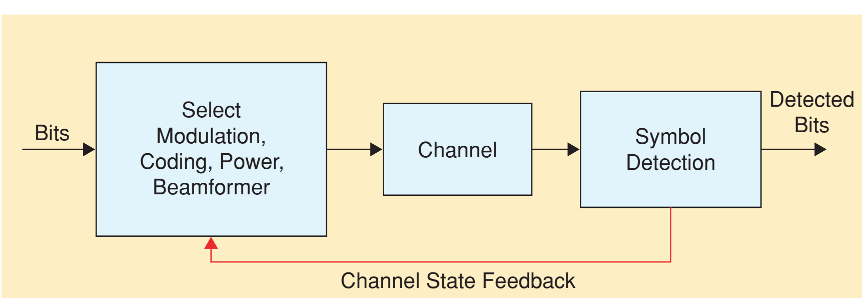
A fundamental limitation to the gains promised by adaptive transmission lies in the acquisition of channel state information (CSI) for resource allocation and transmitter adaptation. This is also true for some transmit diversity and spatial multiplexing systems, which require CSI to optimize transmit power and compute a transmit precoding (or beamforming) matrix or vector. Furthermore, in multiuser time division multiple access (TDMA) systems, CSI is required to schedule the best user based on some scheduling policy. For downlink broadcast systems, CSI is required to cancel or mitigate interference during simultaneous transmission to multiple users. The effort required in CSI acquisition depends on the particular system under consideration. For time division duplex (TDD) cellular systems, the transmitter can infer downlink (forward) channel conditions from an estimate of the uplink (reverse) channel since the same frequency is used in both directions. Therefore, the main problem in CSI acquisition for TDD systems is the channel estimation at the transmitter and the delay before the transmitter resources can be adapted based on the computed channel estimate. Frequency division duplex (FDD) systems present a greater challenge since the forward and reverse channels operate on different frequencies. In FDD wireless systems, downlink rate and/or power adaptation depend on the quality of the channel estimate that is provided by the mobile station (MS) through the reverse (feedback) channel. The channel must be estimated at the MS and transmitted over a feedback channel, which, being a wireless channel, is characterized by bandwidth constraints, fading, and additive noise. The channel fading rate is also of concern because adaptation may be meaningless if the channel changes faster than the transmitter can receive estimates from the MS. Furthermore, channel estimation is limited by the accuracy of the particular estimation scheme that is employed.

In this article, we examine the role that signal processing plays in realizing the benefits of adaptive transmission for FDD systems. We describe in detail the factors affecting CSI acquisition, namely, channel estimation error, feedback delay, quantization error due to bandwidth constraint, and feedback error. In multiuser systems, CSI is required from each user for joint rate and user selection according to some scheduling policy. Here, feedback and quantization errors may cause the scheduler to select a user that is not optimal and/or a rate that is too high given the actual fading level on the channel. We shall discuss the joint effect of quantization and feedback errors on the performance of a TDMA multiuser system.

This article is organized as follows. An overview of adaptive transmission is presented in the following section, including a survey of the research literature on ideal CSI feedback. Then, channel modeling, feedback delay and channel estimation issues and the effect of bandwidth constraints on CSI feedback are presented. The following sections describe the impact and some solutions to feedback channel errors, an extension to multiuser systems, and a discussion on some open problems in adaptive transmission. In the last section, we provide conclusions.

OVERVIEW OF ADAPTIVE TRANSMISSION

The basic principle of adaptive transmission is captured in Figure 1. The objective here is to optimize the system spectral efficiency (SE) subject to a bit error rate (BER) constraint. Toward this end, there are N transmission modes available, namely, $\mathcal{M} = [M_0, \ldots, M_{N-1}]$, which could be some combination of modulation, transmit power, and coding rate. This set $\mathcal{M}$ is available to both the transmitter and receiver. Incoming information bits, $\{b\}$, are mapped to one of these transmission modes based on the transmitter's knowledge of the channel conditions. Given the received CSI, the receiver selects the mode which would maximize the downlink spectral efficiency such that the average or instantaneous BER or packet error rate (PER) is below a target level denoted by BER_t or PER_t. By adapting to the channel conditions, a higher rate is chosen only if the BER is lower than the specified target for the given channel realization. The spectral efficiency of a nonadaptive system can be increased with a higher rate modulation, but this implies that a larger transmit power is required. On the other hand, adaptive transmission systems can get by with smaller power by only increasing transmission rates in favorable channel conditions.



[FIG1] A generic adaptive transmitter with an ideal feedback channel.

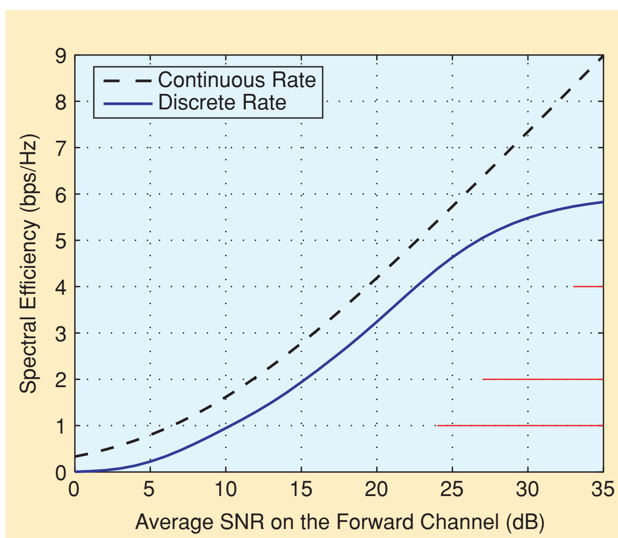
The adaptive transmission concept was first proposed over three decades ago to vary transmission power [3] or symbol transmission rate [4]. At the time, practical implementations may not have been possible given the limitations in the available hardware technology. Secondly, wireless communication as we know it today was practically nonexistent at the time, and that reduced the need for adaptive transmission. With advances in microprocessor technology, the adaptive transmission concept was rekindled in the 1990s with adaptive coding [5] and variable quadrature amplitude modulation (QAM) transmission [6]. Goldsmith and Varaiya [7] presented an information-theoretic foundation for adaptive signaling, showing that the Shannon capacity is achieved with both power and rate adaptation. From a communication theory perspective, a complete analysis of practical power and rate adaptation with all possible degrees of freedom was presented in [8], where all combinations of continuous/discrete power and continuous/discrete rate adaptation were computed for average and instantaneous BER constraints. For multiple antenna systems, AMC in conjunction with diversity combining was shown in [9]. It was shown in [8] that joint rate and power adaptation has only a slight gain compared to only rate adaptation. Thus, we will focus on rate adaptation, and specifically discrete rate adaptation since this is more practical.

THE IMPACT OF FEEDBACK DELAY CAN BE INTERPRETED AS AN SNR LOSS, WHILE FEEDBACK ERROR INTRODUCES AN OUTAGE REGION.

While the literature cited above focused on flat fading channels, there are also results for frequency selective channels (see e.g., [10] for Rake-receiver-assisted AMC systems). An extension of AMC to an orthogonal frequency division multiplexing (OFDM) system was shown in [11]. Incorporating OFDM with AMC raises a new question, namely, how should the power and information bits be allocated to the different subcarriers? This question was investigated in [12], where a loading algorithm is described to optimize the total system spectral efficiency. AMC-OFDM has also been proposed for 3G long term evolution [2]. In interference-limited systems such as cellular systems, a new performance metric, the area spectral efficiency (ASE) was introduced in [13]. With ASE, the authors in [13] show that a tradeoff exists between increasing the communication link spectral efficiency and reducing the interference to other users or cells.

In this article, we consider a wireless system, where the forward channel transmission rate is varied based on short-term or small-scale fading. The MS informs the base transceiver station (BTS) about its channel information via the reverse channel. Initially, we assume that perfect CSI is available to both the transmitter and receiver. For a single-input single-output system (SISO) the received SNR, denoted by γ, is sufficient channel information for rate and/or power adaptation. This is also true for a transmit diversity system such as space time block coding, where the antenna signaling scheme does not depend on channel state information. The MS computes the received power that is required to achieve an instantaneous or average BER constraint ($\overline{\text{BER}}$) [8]. This BER constraint is used to compute a set of SNR thresholds $\mathbf{t} = [t_0, t_1, \ldots, t_{N-1}]$, which correspond to the modes in $\mathcal{M}$, by inverting the BER expression to obtain the required transmit power. The SNR can be quantized into a set of discrete states $\mathcal{S} = [S_0, \ldots, S_{N-1}]$, where $\{S_i : t_i \le \gamma < t_{i+1}\}$. Hence, for $\gamma \in S_i$, the ith mode M_i is transmitted. The threshold computation bears some similarity to scalar source quantization. The difference is that while in source quantization the thresholds are selected to minimize, for example, the mean square error (MSE) [14], in AMC the thresholds are chosen to achieve a target BER constraint. Furthermore, for a time-varying channel there is a time constraint on CSI feedback for rate adaptation to be meaningful. For coded systems, approximate expressions for the instantaneous BER can be obtained by curve fitting of the simulated BER curves [15]. Therefore, without loss of generality, we will focus on rate adaptation for an uncoded QAM-modulated system because the BER expressions are easily obtained.

To illustrate the performance gains offered by AMC, consider a system with four transmission modes, namely, BPSK (1b/s/Hz), QPSK (2b/s/Hz), 16-QAM (4b/s/Hz) and 64-QAM (6b/s/Hz) operating over a flat fading Rayleigh channel. Figure 2 shows the spectral efficiency for an uncoded system over a Rayleigh fading channel with an instantaneous BER constraint. For comparison, the spectral efficiency of a continuous rate system is also shown. There is a 3 dB difference between continuous and discrete rate curves at SE = 4b/s/Hz. This is the price paid by practical discrete rate systems. This performance gap would be smaller with finer quantization, for example, if 8− and 32−QAM are also used. Figure 2 also shows the performance of nonadaptive BPSK, QPSK and 16-QAM signaling (horizontal lines) for $\overline{\text{BER}} = 10^{-3}$. These results are obtained by computing the transmit power required to obtain $\overline{\text{BER}} = 10^{-3}$ for the respective modulations [16], [17]. The average SNR required for 64-QAM, i.e., 6 b/s/Hz, is larger than 35 dB (not shown in the figure) while for the continuous rate system 6 b/s/Hz is achieved with an average SNR of 26.5 dB. Notice that there is an SNR gain of about 14 dB for discrete rate transmission over nonadaptive transmission at 1 b/s/Hz (BPSK), which highlights the significant gain offered by adaptive modulation. There are smaller gains of 12 and 10.5 dB for



[FIG2] Illustration of the spectral efficiency gains offered by adaptive modulation in Rayleigh fading, with $\text{BER}_t = 10^{-3}$.

QPSK and 16−QAM respectively. These gains are achieved by assuming that perfect CSI is available to the transmitter. In the following sections, we discuss the feedback constraints in adaptive transmission and the signal processing techniques that have been proposed to mitigate the performance degradation caused by these feedback constraints.

FOR THE AMC FEEDBACK DETECTION PROBLEM, THE COST OF CHOOSING A HIGH-RATE MODE WHEN A LOWER-RATE MODE IS OPTIMAL IS MORE CRITICAL TO SYSTEM PERFORMANCE THAN SELECTING A LOW RATE WHEN A HIGH RATE MODE IS OPTIMAL.

CHANNEL ESTIMATION AND MODELING

A practical adaptive transmission system is shown in Figure 3. Both the forward and reverse channels h and g are subject to time selective flat fading characterized by the Doppler frequency f_d. The reverse channel is also impacted by feedback delay, denoted by τ, and by feedback errors due to additive noise and fading. Channel estimation is required at the receiver both for symbol detection and for sending the desired transmission mode index to the transmitter. The time variation of the forward channel may be fast enough such that the channel realization would have changed by the time the transmitter can adapt its signaling. A useful measure of this channel variation is the normalized Doppler frequency $f_d T_s$, where T_s is the transmitted symbol duration. In general, feedback delay can degrade the performance of an adaptive transmitter relying on CSI feedback. The impact of a delayed, but otherwise accurate, channel realization was investigated by [16], [18] and [19] for AMC-MIMO. It was shown in [16] that a normalized feedback delay $f_d\tau = 0.01$ can be tolerated without significantly degrading the BER performance when an instantaneous BER constraint is used for threshold computation. For this case, although the transmitter adapts to the delayed CSI it receives, the spectral efficiency is not affected by feedback delay because both the delayed and true CSI have the same statistics [16]. However, the BER performance is certainly worse if a higher rate mode is selected (due to feedback error) when the channel can only support a lower rate mode. It should be clear that a lower rate should be chosen in order to achieve the target BER. This can be accomplished by computing the thresholds using a BER expression that accounts for the feedback delay [20], or using an average BER constraint, e.g., [21]. We now describe some details of channel estimation, which also includes channel prediction.

For a SISO system, let the received signal at the MS be given by

$$y(k) = \sqrt{P_f}\, h(k)x(k) + z_f(k) \tag{1}$$

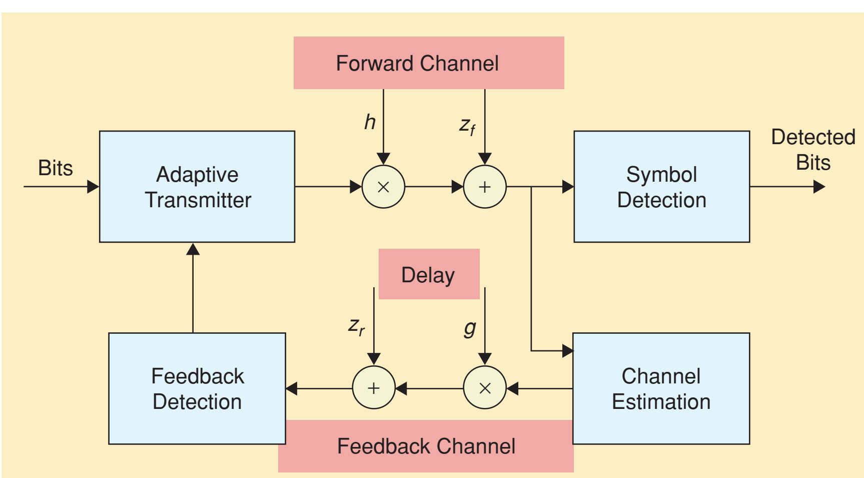
where $x(k)$ is the data symbol with unity average energy, $h(k)$ is the channel realization, z_f is the additive white Gaussian noise, and P_f is the transmitted power (for simplicity, path loss and shadowing effects are included in P_f.) Model-based estimation is typically done by making some assumptions about the channel statistics. For a flat fading SISO channel, the following assumptions can be made:

1) The forward and reverse channels are mutually independent, circularly-symmetric, zero-mean, unity variance, complex Gaussian distributed variables.

2) The channel is temporally correlated. The correlation function $r_{hh}(\tau)$ depends on the normalized Doppler frequency $f_d T_s$.

Two important remarks can be made about the second assumption. First, the correlation between two channel samples decreases with an increase in Doppler or, equivalently, an increase in mobile speed. Hence, for a fixed feedback delay, there is a limit on mobility to realize the gain of rate adaptation. This limit can be relaxed with channel prediction [20]. The maximum feedback delay (or equivalently the maximum mobile speed) that can be tolerated for an AMC system depends on the Doppler estimate. If it is underestimated, this would result in significant degradation. On the other hand, if it is overestimated some spectral efficiency will be lost because the system would not take full advantage of the dynamic range of the channel variation.

To facilitate channel estimation, pilot symbols are inserted with a period, L, in the data stream before transmission; a technique known as pilot symbol assisted modulation (PSAM) [22]. Figure 4 shows the PSAM technique where one pilot symbol is assigned to a block of $L-1$ data symbols. The received signal model is now given by



[FIG3] An adaptive transmitter showing the causes of noisy CSI including feedback delay, fading and additive noise on the reverse (feedback) channel.

$$y_p(kL) = \sqrt{\mathcal{P}_f}\, h(kL) x_p(kL) + z_f(kL) \quad (2)$$

$$y_d(kL + i) = \sqrt{\mathcal{P}_f}\, h(kL + i)\, x(kL + i) + z_f(kL + i), \quad (3)$$

for $i = 1 \ldots L - 1$. Equation (2) is the received pilot signal with a known pilot signal $x_p(kL)$, while (3) describes the $L - 1$ received data signals in each transmitted block. For simplicity, P_f is assumed to be constant for both pilot and data signals but the optimal power allocation between training and data symbols can also be computed (see [20]). Given a length$-J$ observation vector at time kL, $\mathbf{y}_p(kL) = [y_p(kL), \ldots y_p((k - J + 1)L)]^T$, the objective is to estimate the channel at time $kL + \tau$. The value of τ determines the estimation technique: $\tau \leq 0$ implies channel smoothing, while channel prediction is performed when $\tau > 0$. Since the pilot observation of (2) is a linear function of $h(kL + \tau)$, it is straightforward to show that $h(kL + \tau)$ and $\mathbf{y}_p(kL)$ are jointly Gaussian. Therefore, the optimal channel estimate in the mean square error sense is the linear minimum mean square error estimate (LMMSE) of $h(kL + \tau)$. The MMSE for channel prediction depends on the prediction range τ, the filter length J, the pilot power and the Doppler frequency. The prediction error usually results in a conservative choice for the thresholds, i.e., a reduction in the spectral efficiency. The effect of prediction error in MIMO-AMC systems was investigated by [23].

[CSI ACQUISITION IS ALSO IMPORTANT FOR MULTIUSER SYSTEMS TO FACILITATE USER SCHEDULING IN ADDITION TO RESOURCE ALLOCATION AT THE TRANSMITTER.]

FEEDBACK CHANNEL ERRORS

A practical feedback channel is characterized by noise and fading as shown in Figure 3. However, it is commonly assumed in most adaptive transmission schemes that the feedback channel is error-free. This is justified by assuming that a sufficiently powerful error control code can be employed since a low data rate is usually employed for the feedback channel. However, it should be pointed out that for practical feedback schemes, there would still be a nonzero feedback error probability, e.g., the WCDMA standard specifies a feedback BER of 4%. Moreover, the feedback channel reduces the power and bandwidth for the data channels transmitted on the reverse link. This is particularly important since energy conservation is critical for a MS. It should also be noted that decoding time increases with lower coding rates (more parity bits) which in turn increases the feedback delay. This may limit error protection for the feedback channel to simple error control coding schemes. In this section we analyze the impact of noisy feedback channels on the performance of a single user FDD AMC system. Prior work in this area includes the adaptive trellis-coded QAM system of [24], where the feedback information is protected by an error control code. In this section, the feedback channel is characterized by an error probability matrix, which depends on the feedback detection scheme employed. A result of this characterization is that system performance can be shown for any feedback transmission system irrespective of the inclusion, or the lack thereof, of an error control coding scheme. By optimizing the switching thresholds based on an average BER constraint it can be shown [25] that there exists an outage region at low SNR, where adaptive modulation is not feasible.

To focus on feedback channel imperfections, perfect CSI is assumed at the receiver, though some feedback delay τ is allowed. Given that there are N modes available for selection at the transmitter, define

$$\mathcal{U} = \{\mathbf{u}_0, \ldots, \mathbf{u}_{N-1}\}$$

as the set of feedback vectors, where u_i is transmitted to the BTS when the ith index is selected. The impact of the reverse channel can be characterized by an error probability matrix $\mathcal{Q} = [q_{i,j}]$, $0 \leq i, j \leq N - 1$, where $q_{i,j}$ is the probability that M_i is selected for transmission when S_j is the true state. The exact value of $\mathcal{Q}$ depends on the feedback detection scheme employed.

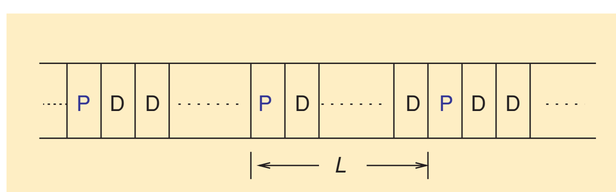
THRESHOLD OPTIMIZATION

In this section we account for both feedback delay and feedback error by computing the SNR thresholds subject to an average BER constraint. The constrained optimization problem can be stated as follows:

$$\max_{\mathbf{t}} \mathrm{SE}(\mathbf{t}) \quad \text{subject to } \overline{\mathrm{BER}} \leq \mathrm{BER}_t, \quad (4)$$

where the optimization variable $\mathbf{t}$ is the SNR threshold vector, and $\mathrm{SE}(\mathbf{t})$ explicitly denotes the spectral efficiency as a function of $\mathbf{t}$. This problem can be solved using the Lagrange multiplier method (see [26 Sec. 6.4.4] for the perfect CSI case and [21] for feedback delay). In [25], the impact of feedback error and feedback delay is shown for an adaptive modulation system. Compared to ideal CSI [26] the existence of a feasible region cannot be guaranteed due to feedback error.

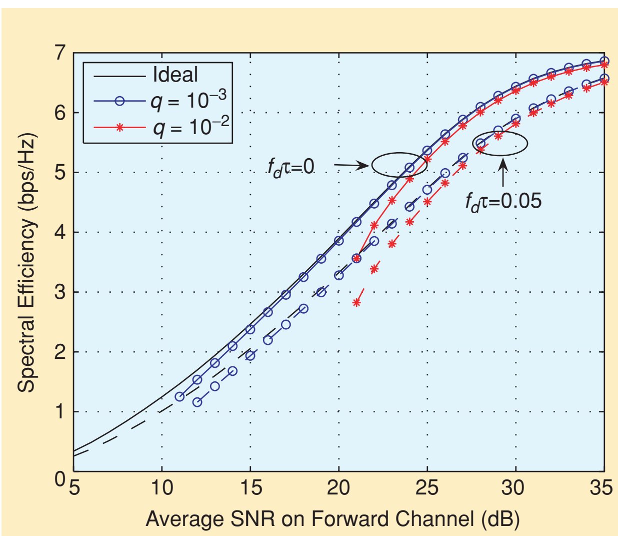
To illustrate the impact of feedback error combined with feedback delay, consider an adaptive modulation system with maximum likelihood detection of the feedback channel, $\mathcal{M} = \{2^i - \mathrm{QAM}\}_{i=1}^{7}$ and $\mathrm{BER}_t = 10^{-3}$. Let q denote the reverse channel BER which is representative of the desired reverse channel quality. Figure 5 [25] shows the spectral efficiency versus the average SNR on the forward channel (in



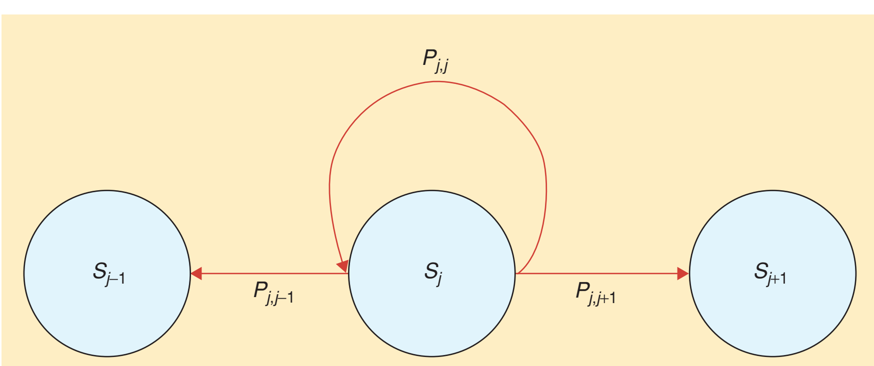
[FIG4] Illustration of pilot symbol insertion for channel estimation. P denotes pilot symbols while D denotes data symbols.

steps of 1 dB) for $q = 10^{-3}$ and $q = 10^{-2}$. The solid lines indicate a normalized delay $f_d\tau = 0$ while the dashed lines are for $f_d\tau = 0.05$. For $q = 10^{-3}$, there is an outage (infeasible) region when $\bar{\gamma} < 11$ dB. This outage region increases up to 21 dB for $q = 10^{-2}$. The existence of an outage region can also be explained by studying the limiting cases of low and high average SNR, $\bar{\gamma}$. As $\bar{\gamma} \to 0$, M_0 is the most likely rate, thus, transmission should be turned off. Feedback error would cause a higher constellation to be transmitted, which significantly increases the instantaneous BER. As a result, the average BER constraint may not be satisfied implying that adaptive modulation is impractical in this region. Conversely, when $\bar{\gamma} \to \infty$, M_{N-1} is the most likely rate, as such, feedback error would not increase the average BER but would reduce the spectral efficiency since a lower constellation is erroneously transmitted. Nevertheless, it is important to note that for high $\bar{\gamma}$, a feasible t can be found to satisfy the constraint of (4).

FEEDBACK CHANNEL AND QUANTIZATION ERRORS WOULD LEAD TO THE TWIN ERROR EVENTS OF ERRONEOUS USER SELECTION AND ERRONEOUS CONSTELLATION SELECTION.



[FIG5] Spectral efficiency for an adaptive modulation system accounting for feedback error and feedback delay.



[FIG6] Illustration of the one-step bounded transition property of the FSMC model.

The impact of feedback delay can be interpreted as an SNR loss, while feedback error introduces an outage region as shown in Figure 5. Since feedback delay affects the true channel state there is a smoother performance degradation compared to feedback error which affects the quantized channel state that is sent to the transmitter. Subsequently, we will consider only the impact of feedback error and we describe feedback receivers that will reduce the outage region.

MARKOV-BASED DETECTION

The Finite State Markov Channel (FSMC) model [27], which is known to be a good approximation to a slow time-selective Rayleigh fading channel, can be used to improve maximum likelihood (ML) feedback detection. The FSMC model has the key feature that state transitions only occur to adjacent states as shown in Figure 6. Mathematically this means that

$$P_{i,j} \triangleq Pr(S(n){=}S_i | S(n-1){=}S_j) = 0 \quad \text{for} |i{-}j| > 1, \qquad (5)$$

where $S(n)$ denotes the channel state at time n and $P_{i,j}$ is the state transition probability. Therefore, for a slowly fading channel, at most three events need to be characterized at each time instant, namely, a transition to the right (higher SNR region), one to the left (lower SNR region), or no change. These properties of the FSMC model were used to design the following feedback receivers [17], [28]: 1) differential feedback—two bits are sufficient to fully describe all channel state transitions, 2) full state feedback of b bits—the feedback receiver can utilize this bounded state transition property to correct some feedback errors. The results of [17], [28] show that the performance loss due to feedback error can be mitigated by employing FSMC-based receivers.

BAYESIAN DETECTION

In most communication systems, transmitted symbols are assumed to be equally likely, implying that a minimum probability of error receiver is equivalent to an ML detector. However, this is not the case for the AMC feedback channel considered here because feedback transmission is coupled to the instantaneous SNR, γ on the forward channel. The state probabilities can be computed at the transmitter if the average SNR $\bar{\gamma}$ is known. This implies that ML feedback detection may be suboptimal to MAP, or more generally, Bayesian detection. The elements of the error probability matrix $\mathcal{Q}$ can be obtained by solving a classical multiple hypotheses testing problem, where the ith hypothesis is defined as

$$\mathcal{H}_i : \gamma \in s_i, \quad i = 0, 1, \ldots, N-1. \tag{6}$$

From detection theory, $q_{i,j} \equiv Pr(\mathcal{H}_i|\mathcal{H}_j)$, which is the probability that the transmitter decides $\mathcal{H}_i$ when $\mathcal{H}_j$ is true. The optimum solution is obtained by minimizing the Bayes risk [29]. The derivation of the feedback error probability is given in [17]. For most Bayesian detection problems $C_{i,j} = C_{j,i}$, where $C_{i,j}$ is the cost of choosing M_i when M_j is the optimal transmission mode. For the AMC feedback detection problem, the cost of choosing a high-rate mode when a lower-rate mode is optimal is more critical to system performance (in term of the BER) than selecting a low rate when a high rate mode is optimal. It makes sense to apply unequal weights that reflect the impact of erroneous decisions on system performance. In [25] a cost factor β is defined such that

BY OPTIMIZING THE SWITCHING THRESHOLDS BASED ON AN AVERAGE BER CONSTRAINT IT CAN BE SHOWN THAT THERE EXISTS AN OUTAGE REGION AT SNR, WHERE ADAPTIVE MODULATION IS NOT FEASIBLE.

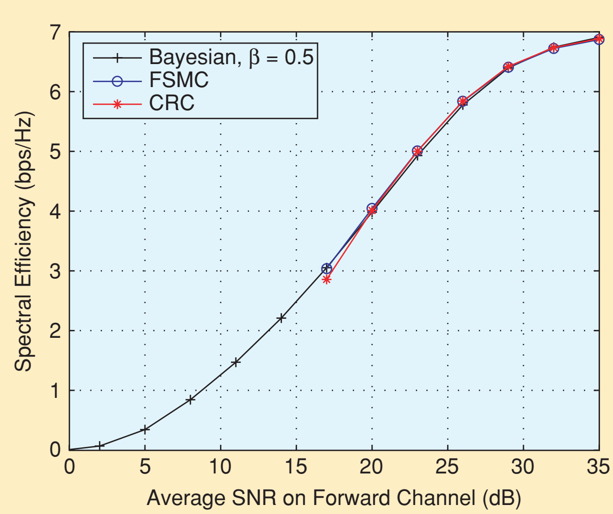
$$\begin{aligned} C_{i,j} &= i - j, \qquad C_{j,i} = \beta\, C_{i,j} \\ 0 \le j &< i \le N-1, \quad \beta \in (0,1]. \end{aligned} \tag{7}$$

We now compare the performance of the Bayesian and FSMC-based feedback receivers for an average BER criterion. For comparison we also consider a cyclic redundancy check (CRC) error detection scheme employing a (7,3) Hamming code. For this CRC scheme, when the feedback information is detected to be in error, it is discarded and the transmission mode is not changed. The error probability matrix $\mathcal{Q}$ is obtained by simulation for the Bayesian, FSMC and CRC receivers and is substituted in (4) to compute the optimal switching thresholds. The performance of these feedback schemes is shown in Figure 7 [25] for $q = 0.01$. The Bayesian receiver with $\beta = 0.5$ eliminates the outage region completely with a negligible drop in spectral efficiency. The FSMC-based receiver compares well with the CRC-receiver and the outage region is reduced by 4 dB compared to the ML detection employed in Figure 5 (see [17] and [25] for more results).

BANDWIDTH CONSTRAINTS

An important question in CSI acquisition for wireless systems is: how much feedback information does the base station or scheduler require for an optimal allocation of system resources to a mobile station? For the single antenna AMC system $b = \log_2 N$ bits is sufficient to achieve maximum spectral efficiency in the absence of estimation and feedback errors. However, it should be noted that the number of feedback bits grows with the number of transmission modes that are employed. For AMC systems [30] computes the number of feedback bits from the channel entropy. For MIMO systems, practical feedback schemes must quantize a channel matrix or vector at the receiver before sending to the transmitter for adaptation. The bandwidth-constrained feedback problem can be stated as follows: *given a finite feedback rate of b bits per channel use, design a codebook $\mathcal{C}$ with cardinality $\|\mathcal{C}\| = 2^b$ to minimize the performance loss compared to perfect CSI feedback*.

An early study of MIMO feedback based on source coding principles was presented in [31]. For equal gain transmission, [32] showed that significant performance could be obtained by quantizing only the relative channel phase information for multiple transmit antennas. A similar technique to this partial phase feedback was standardized for WCDMA closed loop transmit diversity [33]. With the increased focus on MIMO single-user and multi-user systems in the last few years, codebook design with limited CSI feedback has become an active area of research. In [34] codebooks are designed to minimize outage probability. This design criterion is shown to be similar to an SNR maximization design, which was independently proposed in [35]. It was shown in [35] that codebook design can be related to the problem of Grassmannian line packing. Both these schemes assumed error-free feedback channels. A noisy feedback channel is considered in [36] for an orthogonal space-time block coded system. The capacity of MIMO channels with finite rate feedback is studied in [37]. Limited feedback is also of significant interest for OFDM systems particularly when multiple antennas are used because there is now an added dimension of multiple subcarriers. Codebook design can exploit the time-frequency correlation properties of OFDM by grouping correlated subcarriers and only sending back one quantized value for each subcarrier group. This has the potential to significantly reduce the amount of feedback information especially for channels that exhibit a high degree of frequency selectivity, i.e.,



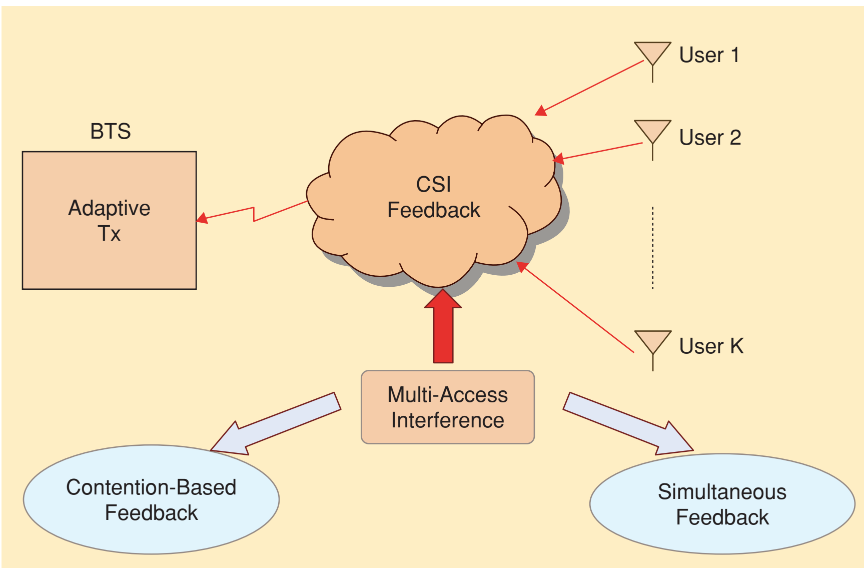
[FIG7] Spectral efficiency for an adaptive modulation system for different feedback detection schemes ($\text{BER}_t = 10^{-3}$, $f_d T_s = 10^{-3}$, $q = 0.01$).

channels with highly correlated frequency bins. Such an approach is taken in [38], where CSI is sent per subcarrier group and the transmitter reconstructs the CSI for all subcarriers using interpolation.

For a MIMO-AMC system, the problem is to design a codebook where the ith index represents a joint selection of rate and precoding vector. This is basically a vector quantization problem [14], which would be familiar to the source coding community. Initial work in this field was by Xia et al. [39], where they use Lloyd-Max concepts to design the codebook. However, the goal here is to optimize the spectral efficiency and not necessarily to minimize the MSE. Recently, the limited feedback problem has been extended to MIMO broadcast systems (see [40] and references therein). In [40] random quantization is used by each mobile to send its CSI to the base station over a low rate feedback channel.

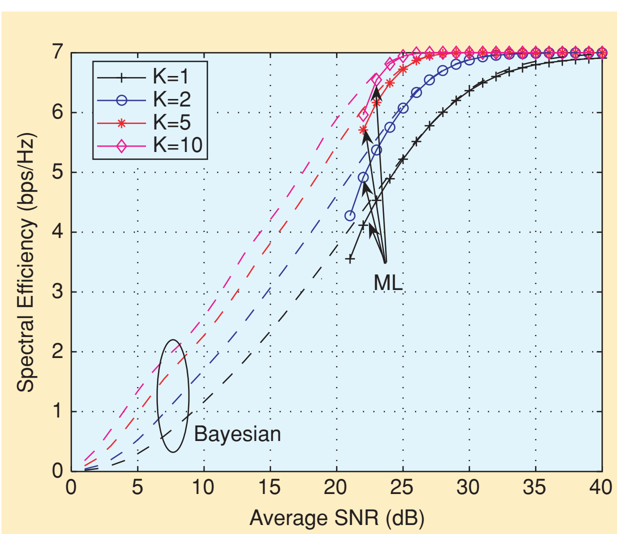
MULTIUSER CSI FEEDBACK

CSI acquisition is also important for multiuser systems to facilitate user scheduling in addition to resource allocation at the transmitter. For downlink (also called broadcast) systems, it has been shown that independence among the channels linking the BTS and a group of users leads to multiuser diversity gain [41], [42], whereby the BTS transmits to the user with the best channel. In addition to the delay, bandwidth constraint and feedback errors described earlier for single user systems, the feedback channel is now interference-constrained as multiple users have to inform the BTS or scheduler about their respective channel estimates.



[FIG8] A multiuser system showing multiaccess interference in the feedback channel.

Research into feedback transfer for multiuser systems has focused on the impact of quantization [43] and on the bandwidth constraint of the reverse channel [44], but possible multiple access interference (MAI) was not explored. This MAI problem was partly addressed in [45] where multiple thresholds are employed so that with high probability only one user may need to send back its CSI information. However, this scheme requires polling between the BTS and the users, and the ensuing delay may not be practical for time-selective fading channels. In [46] multiple antennas and spreading codes are employed to cancel out MAI. For SISO systems, it is shown in [47] that feedback information is proportional to the number of active users in the system. As a result, although, multiuser diversity gain increases with the number of active users, CSI acquisition places a limit on this number.



[FIG9] Spectral Efficiency for an 8-state adaptive modulation system for ML and Bayesian feedback receivers. The system target BER is $\mathrm{BER}_t = 10^{-3}$ **and the feedback channel quality,** $q = 0.01$.

Each user only needs to inform the BTS of the discrete rate it can support given a BER constraint. For a zero-error feedback channel, quantization error may cause the BTS to select a user in the same quantization region as the maximum SNR user. However, in contrast to the capacity results in [43], the spectral efficiency is not affected because the same transmission mode would be selected for discrete rate adaptation. Thus, what is of interest is the combined effect of quantization and feedback errors. Figure 8 shows a TDMA system of K active users, i.e., users for which the scheduler has information to transmit to. After decoding all users' feedback information, the kth user is selected if and only if its requested rate is the highest among all users. In the event of a tie between two or more users, one can be picked with uniform probability [43]. Feedback channel errors would lead to the twin error events of erroneous user selection and erroneous constellation selection. Not only could the requested rate be wrongly decoded, but the selected user may not be the best user.

The combined effect of quantization and feedback error for a zero-delay feedback channel is shown in Figure 9 [17] for $q = 0.01$ and $f_d T_s = 10^{-3}$. The solid lines show the spectral efficiency for $K = 1, 2, 5, 10$ users when ML feedback detection is employed, while the dashed lines are for Bayesian detection. Similarly to the single user case that was shown in Figure 7, there is an outage region at low to medium SNR for ML feedback detection. For $K > 1$ there is the additional effect of wrong user selection, which widens the outage region as K increases. Compared to Bayesian feedback detection, it can be seen that ML detection results in an outage region up to 21 dB for $K = 1, 2$ and increases to 22 dB for $K = 5, 10$. This shows that feedback error has a more serious effect as the number of users increases because of the double effect of wrong user and wrong constellation selection due to quantization and feedback errors. Therefore, a more stringent quality of service is required for thefeedback channel as the number of users increases. For example, the specified feedback BER should be smaller, and/or reverse link power should increase with K.

FEEDBACK ERRORS COULD CAUSE OUTAGE REGIONS WHERE AMC IS NOT FEASIBLE AND COULD ALSO IMPACT THE BENEFITS OF MULTIUSER SCHEDULING.

OPEN PROBLEMS

1) Channel modeling errors: the conventional statistical models adopted for channel estimation may be inadequate for a specific wireless scattering environment. Much of the channel estimation work for AMC has assumed the Jakes' isotropic scattering channel model [48]. While the Jakes model is robust, it may be overly pessimistic in some wireless environments because the assumption of uniform scattering may be valid only for rich scattering environments such as urban microcells. Abdi et al. [49] have shown that a different angle-of-arrival distribution, modeled on the von Mises probability density function (pdf), is realistic in some wireless environments.

Other modeling errors are possible. For example, Nakagami fading channels are characterized by the Nakagami parameter m, where $m = 1$ for the Rayleigh channel. The Rayleigh channel is the worst case in terms of spectral efficiency [16] Therefore, if the thresholds are computed based on a Rayleigh channel some gain is lost if $m > 1$. It may be worthwhile to investigate the impact of channel uncertainty/modeling errors on AMC systems.

2) Energy minimization: very little work has been done to quantify the amount of energy expended for feedback transmission. A different design objective may be to compute the switching thresholds to minimize the energy used for feedback.

3) Multiuser feedback: we have considered the TDMA case, where only one user is scheduled at any time instant. This could be extended to multi-antenna broadcast systems, where transmission is scheduled to more than one user simultaneously.

4) MIMO-AMC feedback: quantized CSI for rate and precoding selection can be studied for spatially correlated channels, feedback delay and feedback error.

5) OFDM systems: our studies on the impact of feedback error could be extended to multicarrier systems. For such systems, a dual problem to the forward channel is also evident for feedback channels, i.e., how should feedback bandwidth and power be allocated to send CSI estimates of each subcarrier to the BTS?

CONCLUSIONS

In this article, we have presented the feedback constraints that limit the potential of AMC and MIMO systems for FDD systems. It has been shown that while adaptive transmission efficiently utilizes the available bandwidth and transmit power, feedback constraints could be a significant impediment. Channel prediction can be employed to compensate the impact of feedback delay but its effectiveness would depend on the accuracy of the channel model. We also showed that feedback errors could cause outage regions where AMC is not feasible and could also impact the benefits of multiuser scheduling. Limited feedback is a major issue for MIMO-AMC systems because channel state information grows with the rank of the MIMO system, the number of transmission modes, and the number of users for broadcast systems. Since feedback transmission consumes resources that could otherwise be used for data transmission on the reverse channel, feedback design is extremely important especially for power-limited devices such as mobile stations. Finally, we outlined some open problems that are of interest to adaptive transmission systems.

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