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Full Length Research Paper

Adaptive real time wireless data transmission using superposition coding with feedback of channel state information

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High quality data transmission services are an important issue for broadband wireless access (BWA) systems. This paper deals with the design issues of a real-time wireless data transmission which provides unequal error protection (UEP) over an additive white Gaussian noise (AWGN) channel. Traditionally, transmission is made from a one bit stream at one level of power (for example, pulse amplitude modulation (PAM)) but using different techniques to exploit the available bandwidth. Using superposition coding, the real time data bit stream can be divided into two bit streams. The first bit stream represents the region of high priority (HP) while the second represents low priority (LP) region. These two bit streams are modulated separately, and superimposed together with two different levels of power to achieve the UEP at the receiver side. Feedback of the channel state information (CSI) is used by adaptive channel in the physical layer such that the current available bandwidth is used efficiently. In this proposed scheme, the same design metrics, namely time, bandwidth and power are used to increase the transmission efficiency. The performance of the proposed scheme is compared with the traditional, 2-PAM and 4-PAM schemes. Unlike the traditional schemes, the results show that our scheme provides a higher data rate at an acceptable bit error rate (BER) when the channel is in good condition. When channel quality is degraded, a reduced data rate is applied in contrast with the traditional schemes. As compared with the traditional 4-PAM scheme, the proposed scheme gives a good error performance for the HP bit stream with 0.2 dB gain increase at BER of 10^{-5}, and exhibited a 4 dB gain when the channel condition is bad.

Key words: Superposition coding, real time transmission, UEP, CSI, AWGN.

INTRODUCTION

The main challenge in future broadband wireless access (BWA) systems are to transmit error-sensitive application data with a higher bit rate efficiently over error prone wireless channels. One of the effective methods of accomplishing this is to use unequal error protection (UEP), which provides different levels of protection against the error to various parts of the data with unequal degree of importance (Yang et al., 2004). For example in the case of video conferencing, people usually concentrate on the participants rather than the background. The perceived quality would be better if the area of interest could be allocated more resources than the area that is not of interest. Hence, the distribution of errors can be improved by using UEP without exploiting extra resources.

In UEP, the application data stream is divided into two bit streams, high priority (HP) and low priority (LP) bit streams according to different priorities. The HP bit stream carries the most important data while the LP bit stream carries the less important data. Unlike LP data, the errors in the HP data must be kept as low as possible because it has a significant effect on the quality of the rebuilt application data (Cover, 1972; Bergmans and Cover, 1974; Cover, 1998; Gadkari and Rose, 1999;

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Cronie, 2007). A sub-channel partitioning based-UEP scheme for a space-time block coded orthogonal frequency division multiplexing (STBC-OFDM) system is proposed by Yang et al. (2004). At the receiver side of this system, the sub-channels are partitioned into high-quality (HQ) and low quality (LQ) groups according to the estimated channel qualities. Thus, the transmitter assigns HP and LP video data to the corresponding HQ and LQ sub-channels respectively based on the feedback of the sub-channel partitioning result.

A superposition coding scheme has been proposed by Cover (1972) and Bergmans and Cover (1974). This coding scheme involves the subtraction from the received signal of the estimated signal sent by the other transmitters, followed by decoding of the intended signal such that it can be exploited together with UEP. The superposition coding modulation (SCM) scheme that uses block codes as its component code has been proposed by Karabulut and Yongacoglu (2003) as a superposition block coded modulation (SBCM). It shows that SBCM can achieve a significant gain from low encoding and decoding complexity to high flexibility of UEP design. A coding rate design with UEP requirements for SCM schemes is proposed by Karabulut and Yongacoglu (2004) by pointing out the similarities between a multiple access channel and the SCM system. Moreover, this systematic technique enables the reliable and energy efficient delivery of multiple scalable video stream motion JPEG 2000 over a wireless local area network (WLAN), as was introduced by Xin et al. (2006).

The channel state information (CSI) feedback of the current channel characteristics can give more moderate resources allocation since there is good information about the available channel bandwidth. Wong and Kwok (2004) proposed that the real time video data be divided into two regions; a region of interest (ROI) and a remainder region (RM). These two regions of video data will be encoded adaptively to the current channel state, whereby the channel state parameters are fed back to the source encoder to adjust the compression ratio of both regions.

In this paper, we propose a new technique in order to get guaranteed high quality reception for the HP bit stream even under bad channel condition. On the transmission side, the source data is divided into two bit streams; the HP and LP bit streams. More degrees of protection are assigned for the HP bit stream against the errors that may occur during the data transmission in an error prone environment. These two bit streams with two different levels of protection are superimposed together and sent to a multi-stage decoding (MSD) receiver over an additive white Gaussian noise (AWGN) channel. At the receiver side, the HP and LP bit streams are decoded in two stages separately. Since the HP bit stream has a high level of error protection, the receiver will first decode it and subtract it from the received signal, while the data of the LP bit stream is decoded in the second stage. The system encodes, modulates, sends and decodes these two bit streams or just the HP bit stream depending on the feedback of the CSI.

In order to achieve more protection for the HP bit stream, this work should assign more available resources to the HP bit stream than the LP bit stream. Moreover, another degree of protection for the HP bit stream is proposed in this work whereby the modulation degree will be switched to a stronger level to guard this bit stream against the corruption of the transmitted channel when the channel is in a poor state. Without loss of generality and to simplify the performance analysis of our scheme, the system changes from 4-PAM to 2-PAM when the channel state changes from a good to poor condition and vice versa. The results show that the performance is significantly improved in both data rate and error performance for real-time wireless data transmission. Also, the results show that a better performance can be obtained when the transmitted signal has uniform constellation.

SUPERPOSITION CODING SCHEME WITH AN UNEQUAL ERROR PROTECTION

UEP is an effective technique for wireless data transmission over error-prone channels Muhammad et al. (2010). The different levels of protection are provided for different parts of the data according to their different degrees of importance. There are several approaches to achieving UEP for data transmission. For example, the sub-channel partitioning based UEP scheme for the STBC-OFDM system has been proposed by Yang et al. (2004). In such scheme, the video data is partitioned into HP and LP layers according to the importance of the data. Two transmit antennas will be used to provide two uncorrelated multipath channels corresponding to the HP and LP layers as shown in Figure 1. At the receiver side, one or more receiver antennas are used to receive such HP and LP data. With the assumption of constant channel response, these STBC data of the HP and LP layers will be performed corresponding to two consecutive OFDM symbols.

Other classes of UEP schemes have been proposed by Gadkari and Rose (1999), such as time-division coded modulation (TDCM) and SCM. These classes of UEP are based on their type of application. The coded signal will be transmitted over a channel whose precise characteristics are not known to the transmitter. Such communication channels include broadcast and mobile communication channels without a feedback path from the receiver to the transmitter.

In the case of mobile communication systems, if the information of the time-varying channel characteristics is not available at the transmitter, the encoding operation would consider a range of possible channel conditions that the receiver may experience. This is quite similar to

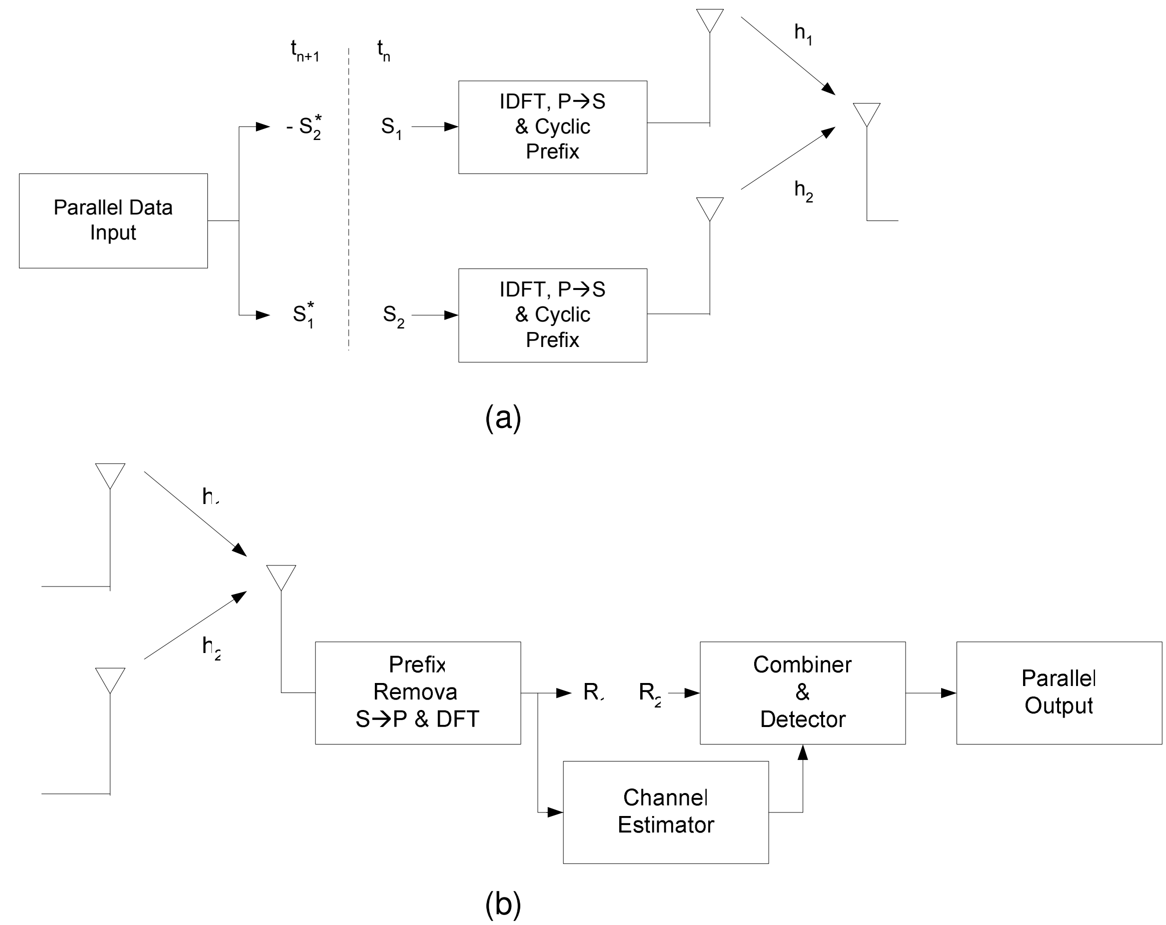

Figure 1. An STBC-OFDM system: (a) transmitter; (b) receiver.

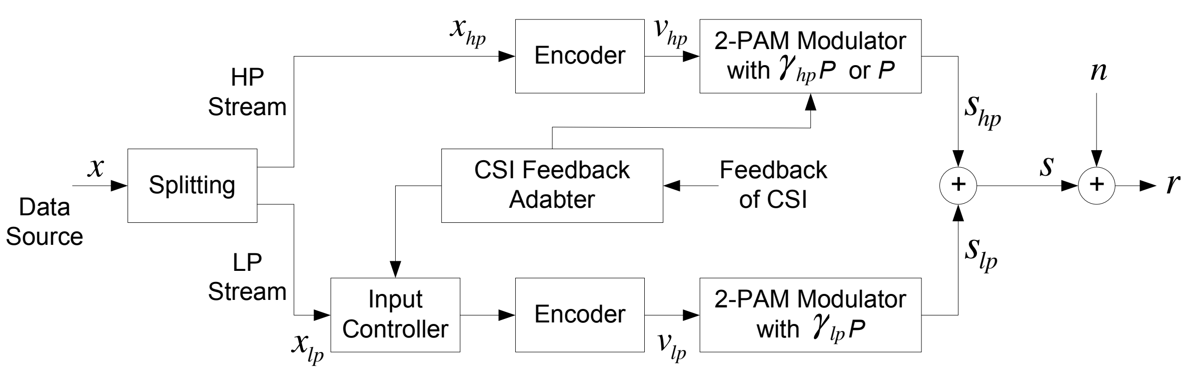

Figure 2. Adaptive channel transmissions scheme.

the broadcast case.

In TDCM, the bit streams of differing importance are transmitted on disjoint modulation intervals. The different bit streams are transmitted on the same modulation intervals in SCM. It has been shown by Bergmans and Cover (1974) that SCM always outperforms TDCM.

SYSTEM DESIGN WITH CSI FEEDBACK

The block diagram of the adaptive channel transmission is shown in Figure 2 which consists of five major components; splitting circuit, encoding circuit, modulator, CSI feedback adapter (CFA) and input controller. In the

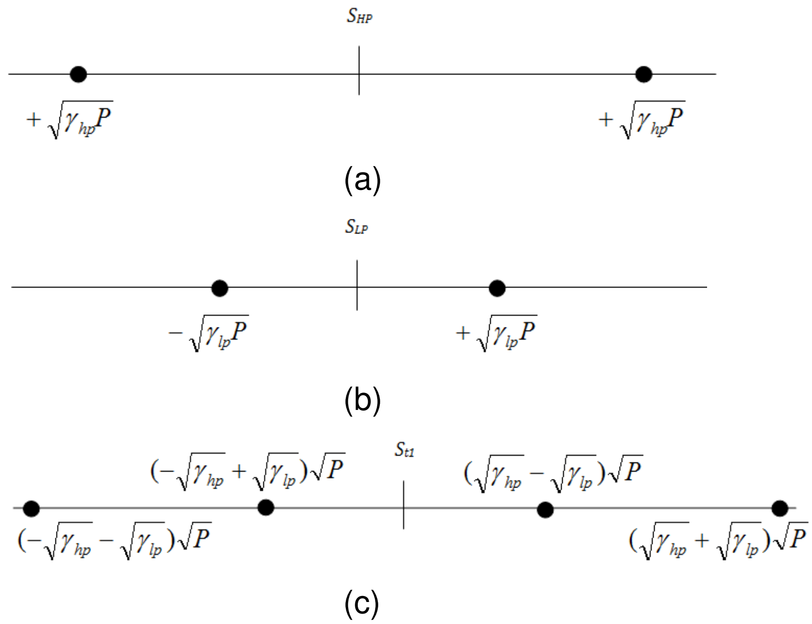

Figure 3. Transmitted signal constellations of: (a) HP bit stream, (b) LP bit stream and (c) GCM transmitted signal.

stage of the adaptive transmitter, the source data is split into two bit streams, HP and LP bit streams, according to their data priorities.

After the splitting stage, two system modes; good channel mode (GCM) and bad channel mode (BCM) will be introduced depending on the output of CFA block. This CFA block makes a decision on whether GCM or BCM will be used according to the feedback signal of CSI from the receiver. The GCM is chosen as a default mode or when the channel is in good condition, while the BCM will be chosen when the channel is in bad condition or no CSI signal is detected. In other words, let N be the Gaussian noise with zero mean, while N_{hp} and N_{lp} denote the prescribed variances of the Gaussian noise that the respective HP and LP bit streams are required to withstand respectively. It is assumed that $N_{hp} > N_{lp}$. If $N_{lp} < N < N_{hp}$, only the HP bit stream is reliably decoded where the system is in BCM. If $N < N_{lp}$, then both HP and LP bit streams are reliably decoded where the system is said to operate in GCM. The mechanism of the system operation as well as the protocols between the system components of GCM and BCM in both transmitter and receiver sides will be described in the following subsections.

GCM ($N < N_{lp}$) at the transmitter side

Initially the system will be operated in GCM mode as default mode or when the CSI feedback signal shows that the channel is in a good state. As shown in Figure 2, the modulator in the HP branch uses its designed fraction of power, γ_{hp} to modulate the HP bit stream. The signal constellation of this modulator, S_{HP} is illustrated in Figure 3a. The LP branch is then set as an active branch by the input controller. Thus, the LP bit stream will be modulated and sent with γ_{lp} fraction power where $\gamma_{hp} + \gamma_{lp} = 1$ and $\gamma_{hp} > \gamma_{lp}$. The signal constellation of LP bit stream, S_{LP} is illustrated in Figure 3b. As a result, after the summing node, the constellation of the transmitted signal of this mode, S_{t1} consists of four symbols (4-PAM) as shown in Figure 3c.

As shown in Figure 2, when the system is in GCM, the bit streams, x_{hp} and x_{lp} are encoded separately to generate v_{hp} and v_{lp} codewords. This codewords are modulated as s_{hp} and s_{lp} signals for the constellations mapping as shown in Figure 3. These modulated signals are then superimposed together before transmitted over the AWGN channel as

$$s = s_{hp} + s_{lp} \tag{1}$$

At the receiver side, the received sequence is

$$r = s + n \tag{2}$$

where n is a sequence of independent identically distributed (i.i.d) Gaussian noise with zero mean and

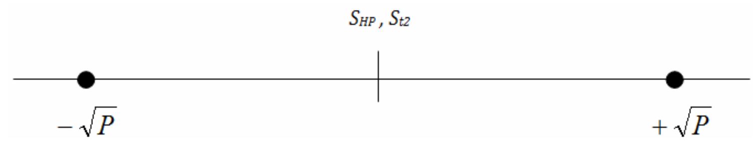

Figure 4. Transmitted signal constellations of HP bit stream, S_{HP} and BCM transmitted signal, S_{t2}.

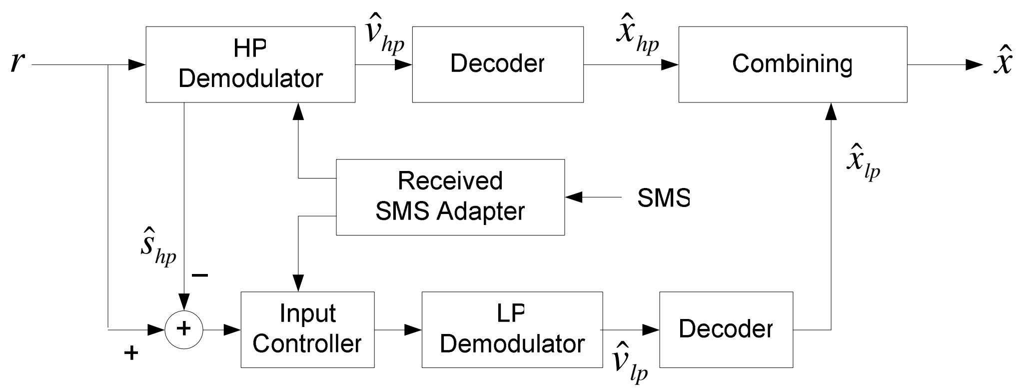

Figure 5. MSD receiver scheme.

variance *N*.

BCM ($N_{lp} < N < N_{hp}$) at the transmitter side

The BCM mode is chosen by the CFA when the CSI feedback signal shows that the channel is in a bad state or no CSI signal is detected. Depending on the CSI condition, the LP branch is set as idle (that is, the LP bit stream will be not sent) by input controller. Therefore, it is not necessary to assign power to LP bit stream in this mode. Thus, the total available transmitted power, *P* will be assigned to HP modulator. The constellation of transmitted signal, S_{t2} in this mode consists of two symbols (2-PAM) and is similar to that for HP bit stream, S_{HP} of this mode as shown in Figure 4.

In other words, if the system is in BCM, only the x_{hp} bit stream will be encoded to generate v_{hp} codeword. Then, the v_{hp} is mapped to the constellation S_{HP}. Thus, the transmitted signal, s consists only of HP modulated signal, s_{hp} as

$$s = s_{hp} \tag{3}$$

The received sequence at the frontage of the receiver become

$$r = s + n = s_{hp} + n \tag{4}$$

In the same manner, the operation protocols in both GCM and BCM will be discussed separately from the viewpoint of the receiver later on.

GCM ($N < N_{lp}$) at the receiver side

The receiver design of the proposed scheme is shown in Figure 5. By sending synchronous mode signal (SMS) over the channel from the transmitter, the receiver will be notified about the chosen mode synchronously to determine which signal constellation, S_{t1} or S_{t2} (see Figures 3 and 4) will be used in the demodulation stage. In the GCM mode, both HP and LP branches are active. In order to estimate the transmitted HP and LP bit streams, an MSD procedure can be used. Since we have two bit streams, the transmitted information will be decoded by the two-stage MSD receiver. In the first stage, it decodes the data of the HP bit stream, $\hat{x}_{hp}$ with highest error protection while treating the signal from the LP bit stream as Gaussian interference. Once the receiver decodes the data of the HP bit stream, it can reconstruct the modulated signal of this bit stream, $\hat{s}_{hp}$ and subtract it from the received signal, *r*. In the second stage the receiver can decode the data of the LP bit stream, $\hat{x}_{lp}$ and then only the background Gaussian noise is left in the system. The combining circuit is used to combine both of the decoded bit streams to reconstruct the transmitted data source, $\hat{x}$ as

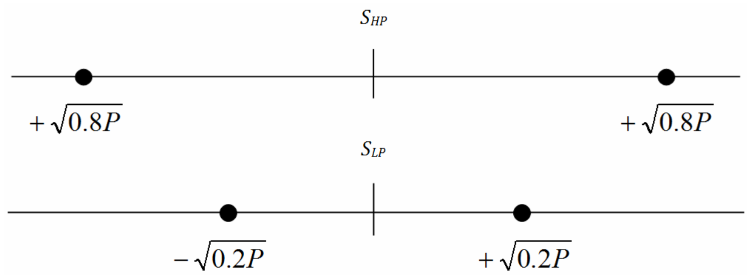

Figure 6. Signal constellation of HP bit stream and LP bit stream for GCM.

$$\hat{x} = \hat{x}_{hp} + \hat{x}_{lp} \tag{5}$$

BCM ($N_{lp} < N < N_{hp}$) at the receiver side

Depending on the SMS signal, the receiver can change its mode from GCM to BCM in synchronous manner with the transmitter. The input controller sets the LP branch in Figure 5 as idle branch depending on the signal that comes from the received SMS adapter (RSA). At the same time, the total available power is assigned to HP demodulation. Thus, only the HP decoded branch is remained as active in the system. In other words, only HP bit stream, $\hat{x}_{hp}$ is reliably demodulated. Consequently, a one-stage decoding procedure will be used. The receiver in this mode decodes the data of the HP bit stream, $\hat{x}_{hp}$ which carries most important data when only the background Gaussian noise is left in the system and there is no signal interference from the LP bit stream. Since the LP bit stream, x_{lp} carries low important data, the system provides the guaranteed continuance of reasonable reception even without decoding this bit stream. Thus, the reconstructed transmitted data source is given as

$$\hat{x} = \hat{x}_{hp} \tag{6}$$

SIMULATION RESULTS

Consider the application data source that produces a bit stream with high quality requirements to be transmitted through a AWGN channel. For high spectral efficiency transmission, the proposed scheme is operated in two modes; GCM and BCM depending on the CSI feedback signal. Without loss of generality, assume that the CSI is perfectly available at both receiver and transmitter. Consequently, the system will be in GCM at the beginning of the system's operation or when the feedback signal of CSI from the receiver shows that the channel is in a good state. To achieve UEP levels in this mode, the total available transmitted power, *P* in the modulation stage is divided unequally between the HP and LP bit streams. Let the fractions of power become 0.8*P* and 0.2*P* assigned to the HP and LP bit streams respectively (that is, γ_{hp} = 0.8 and γ_{lp} = 0.2). With these fractions of power, a uniform signal constellation can be achieved. Then, the v_{hp} codewords are modulated by a 2-PAM modulator using the S_{HP} signal constellation, while for the v_{lp} codewords, another 2-PAM modulator is used for the S_{LP} signal constellation as shown in Figure 6.

In the case when the channel is in a bad state or the feedback signal of CSI is not detected, the LP branch will be in idle state and the BCM will be selected. Thus, the total average transmitted power, *P* is assigned to the HP bit stream only (that is, γ_{hp} = 1 and γ_{lp} = 0). The constellation of HP for the 2-PAM modulator signal, S_{HP} for BCM is shown in Figure 4.

After the summing node as shown in Figure 2, depending on the feedback signal of CSI, either the 4-PAM or 2-PAM transmitted signal constellation will be selected. Therefore, the available bandwidth will be exploited as shown in Figures 7a and b for the GCM and BCM respectively. As shown in these figures, S_{t1} is the signal constellation of the GCM state, so that a high data rate with the most spectral efficiency is transmitted through the available bandwidth. While in the BCM state, a low data rate is transmitted using the S_{t2} constellation with the least spectral efficiency of the HP bit stream only by using all the available power.

The signal constellation mappings are conducted by using Gray encoding for the transmitted signal, *s* of GCM and BCM which has been described in Equations 1 and 3 respectively. This signal, *s* will be sent to the receiver over the (0, N) AWGN channel. At the receiver side, one of the two operating modes: GCM or BCM will be selected by RSA depending on the SMS signal. If the GCM is selected, then the LP branch will be active and the MSD procedure will be used to decode and demodulate the received signal, *r* in two stages. First, the HP bit stream, $\hat{x}_{hp}$ is decoded and used in the second stage for the LP bit stream decoding. The result of subtracting the $\hat{s}_{hp}$ signal from the received signal, *r* is then analyzed by an LP demodulator to estimate the LP bit

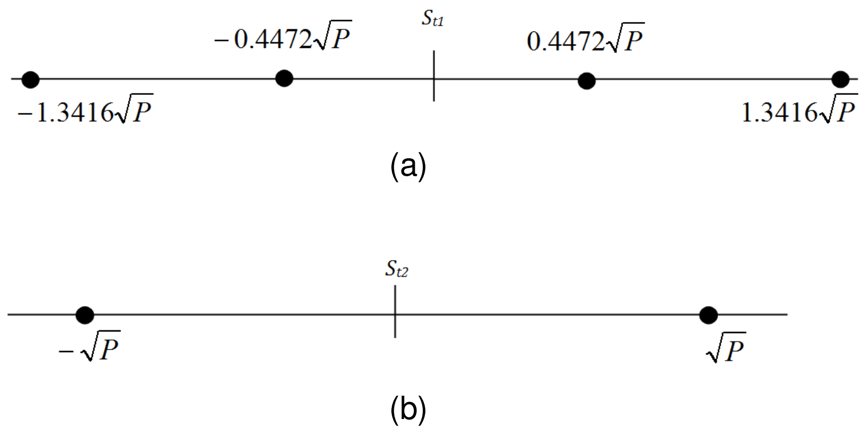

Figure 7. Transmitted signal constellations at: (a) GCM at γ_{hp} = 0.8, and γ_{lp} = 0.2 (that is, uniform constellations), and (b) BCM at γ_{hp} = 1, and γ_{lp} = 0.

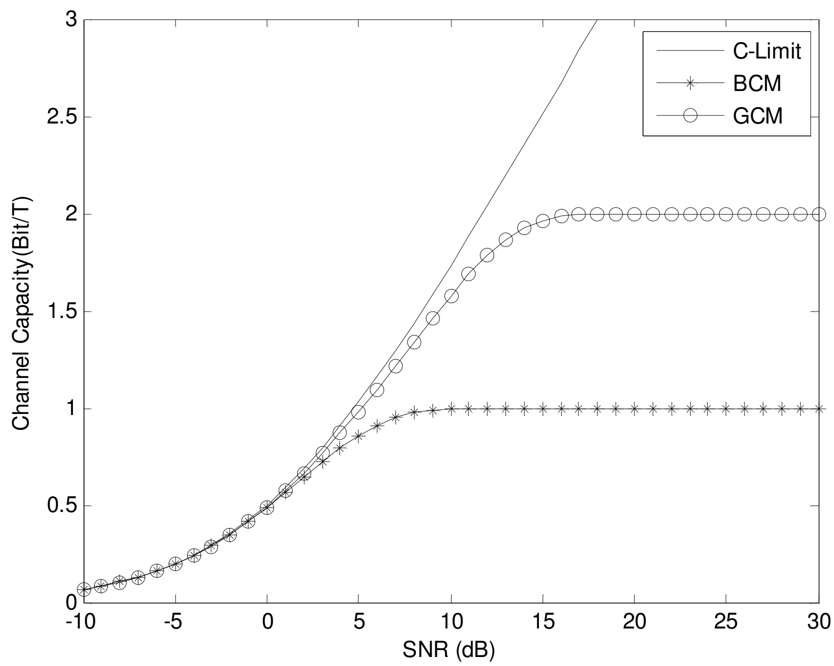

Figure 8. Channel capacity of adaptive transmissions using superposition coding of UEP bit streams.

stream, $\hat{x}_{lp}$. The estimated data from the two stages of decoding, $\hat{x}_{hp}$ and $\hat{x}_{lp}$ are combined to reconstruct the original transmitted data, $\hat{x}$. On the other hand, if the system is in BCM, only the HP bit stream, $\hat{x}_{hp}$ is decoded. The LP branch will become idle due to the signal indicated from RSA as illustrated in Figure 5. Therefore, the received signal in this mode is described in Equation 4 and only the first stage of the earlier discussed MSD receiver is used to reconstruct the transmitted HP data, $\hat{x}_{hp}$ without any interference from the LP data signal.

The comparison of channel capacity of the proposed scheme for the GCM and BCM modes with channel limit capacity, C-Limit is done where the C-Limit is given as

$$\text{C - Limit} = 0.5\log(1+\text{SNR}) \tag{7}$$

The results for different values of the signal to noise ratio (SNR) for this comparison are shown in Figure 8. It is

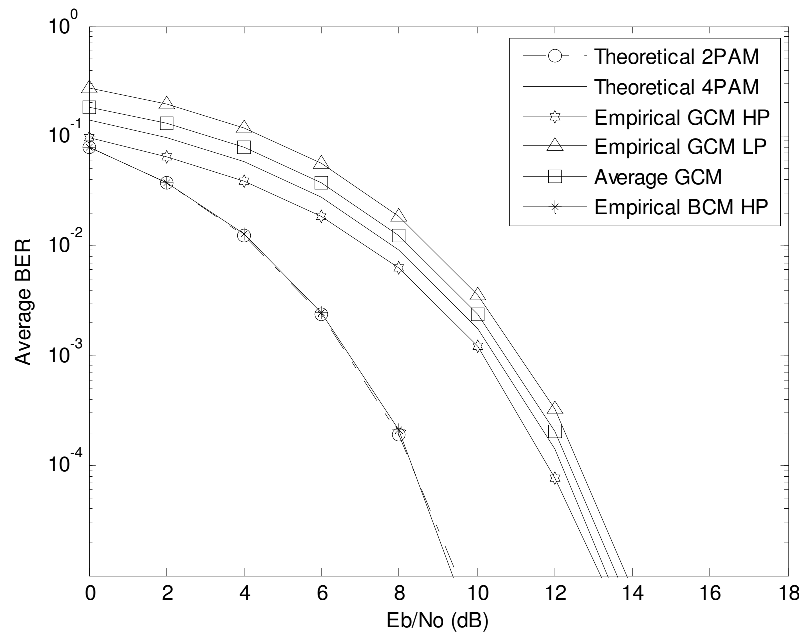

Figure 9. BER comparison between empirical HP and LP bit streams with the theoretical 2-PAM and 4-PAM.

clear from these results that a high spectral efficiency is produced in the region of SNR > 15 dB. For GCM, 2 bits per transmission can be achieved. In this case, the system performance is close to the channel limit in the range of SNR < 10 dB. Further, 1 bit per transmission can be achieved for a BCM instead of no transmission as in traditional schemes when the channel is poor (Figure 8).

The bit error rate (BER) performance of the proposed scheme is given in Figure 9. The curves of the HP and LP bit streams as well as the average of them are shown and compared with the BER of traditional 2-PAM and 4-PAM schemes in both GCM and BCM. As seen in this figure, if the channel is in a good state, the proposed scheme outperforms the traditional 4-PAM modulation for higher error protection of HP bit stream with 0.2 dB gain at a BER of 10^{-5}. Also, there are just 0.5 dB and 0.3 dB as expensed for the less error protection of LP bit stream and the average of both bit streams respectively. In the case of no feedback signal detected or in a bad channel condition, the proposed system will only transmit and decode the HP bit stream. The performance is exactly the same as in 2-PAM modulation where a BER of 10^{-5} is achieved at a SNR of 9 dB. As a result, the LP bit stream does not affect the performance of the received data while the reception for the HP bit stream is continually maintained.

The performance of the proposed scheme in GCM is evaluated for three different scenarios of UEP where the different power fractions are assigned to HP and LP bit streams. The results of average BER of HP and LP bit streams are compared with the traditional 4-PAM as illustrated in Figure 10. It is clear that the performance of uniform constellation, (γ_{hp} = 0.8, and γ_{lp} = 0.2) is better than the other two UEP scenarios. As shown in this figure, for the uniform constellation, the performance of the proposed scheme outperforms others irregular constellations, (γ_{hp} = 0.85, and γ_{lp} = 0.15) and (γ_{hp} = 0.75, and γ_{lp} = 0.25) with 1.2 and 1.5 dB gain respectively (Figures 9 and 10).

From the result, the proposed scheme introduces guaranteed continuous reception for the HP data even if the channel was in bad condition. Since the LP bit stream carries the low important data, the effect of its absence on the reception quality at the receiver side was invisible. Consequently, all available bandwidth in the real time communication systems was exploited to transmit the HP data instead of no transmission in the traditional schemes during bad channel condition. On the other hand, it provided a higher data rate with an acceptable BER for both HP and LP bit streams when the channel was in a good condition. Also, the performance of the proposed scheme depended on the power fractions that were assigned to each bit stream. Therefore, these power fractions must be chosen carefully in the transmitter side.

Conclusion

To meet the emerging requirements of wireless data transmission in real time communication systems, with a high error protection, is a challenging goal. This paper

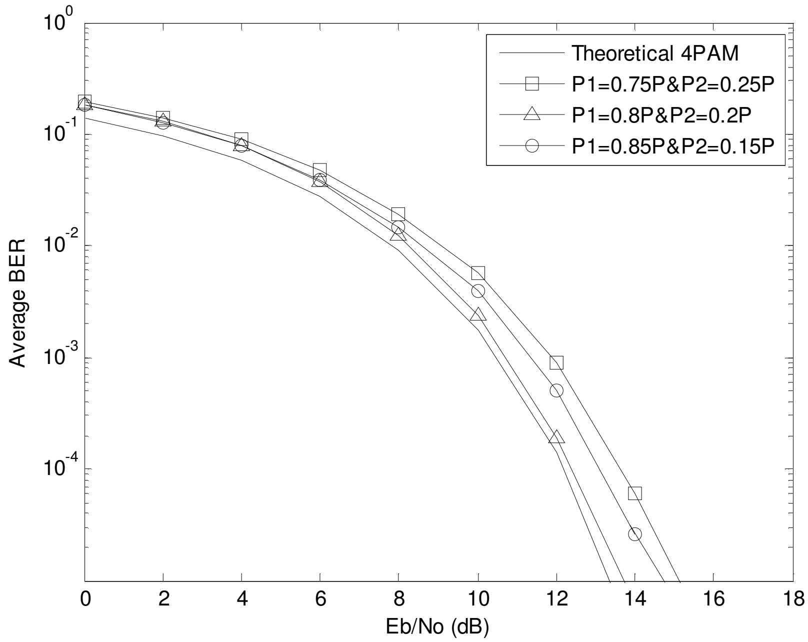

Figure 10. BER comparison of regular and irregular transmitted signal constellations.

has proposed a scheme for the continuous real time transmission with different levels of error protection which are assigned to the different level priorities of data. Superposition coding and CSI was employed for this purpose. By splitting the information data into two parts depending on their importance, the proposed scheme focuses on how the modulators and the superposition coding technique reacts with known CSI. Based on the available channel bandwidth, LP information data are sent or dropped to manage continuous transmission for HP information data with the best available quality. Adaptive transmission is achieved in this proposed system by using the feedback of the CSI to exploit the available resources (time, power and bandwidth). The system performance of the proposed scheme is compared with the traditional transmission schemes and it shows good and flexible performance. The performance of the system in fading environments is left for future work.

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