NEAR-INSTANTANEOUSLY ADAPTIVE COOPERATIVE SCHEMES BASED ON MULTI-LAYER SPACE-TIME BLOCK CODES

Mohammed El-Hajjar†, *Salam Zummo*‡ *and Lajos Hanzo*†

† School of ECS, University of Southampton, SO17 1BJ, UK.
Email: {meh05r,lh}@ecs.soton.ac.uk, http://www-mobile.ecs.soton.ac.uk
‡ Electrical Engineering Department, King Fahd University of Petroleum and Metal (KFUPM),
Dhahran, 31261, Saudi Arabia, Email: zummo@kfupm.edu.sa

***Abstract* - In this paper we propose two adaptive schemes for improving the achievable throughput of cooperative diversity aided wireless networks. These schemes are capable of accommodating the channel signal-to-noise ratio (SNR) variation of wireless systems by near-instantaneously adapting the uplink transmission configuration. Explicitly, the first adaptive transmission scheme is constituted by a novel reconfigurable multilayered space-time block code (MLSTBC) structure. By contrast, the second adaptive scheme is constituted by a reconfigurable vertical Bell Labs Layered Space Time (V-BLAST)-like architecture. Our results demonstrate that significant effective throughput improvements can be achieved by both systems, while maintaining a target bit-error-ratio of 10^{-3}. Explicitly, the first system is capable of attaining an effective throughput varying between 1 bit-per-symbol (BPS) and 8 BPS, while the second has a throughput varying between 2 BPS and 8 BPS.**

1. INTRODUCTION

The fundamental limitations of reliable wireless transmissions are imposed by the time-varying nature of the typical multipath fading channels, which may be efficiently circumvented by sophisticated transceiver design [1] employing multiple antennas at both the transmitter and the receiver. Recent information theoretic studies [2, 3] have revealed that employing a multiple-input multiple-output (MIMO) system significantly increases the capacity of the system. In [4], Wolniansky $et\ al.$ proposed the popular multi-layer MIMO structure, known as the Vertical Bell Labs Layered Space-Time (V-BLAST) scheme. The V-BLAST receiver is capable of providing a tremendous increase of a specific user's effective bitrate without the need for any increase in the transmitted power or the system's bandwidth. However, its impediment is that it was not designed for exploiting transmit diversity and the decision errors of a particular antenna's detector propagate to other bits of the multi-antenna symbol, when erroneously cancelling the effects of the sliced bits from the composite signal.

Whilst V-BLAST was designed for maximising the achievable multiplexing gain, Alamouti [5] discovered a witty transmit diversity scheme, referred to as a space-time block code (STBC), which was designed for a high diversity gain. The attractive benefits of Alamouti's design motivated Tarokh $et\ al.$ [6] to generalise Alamouti's scheme to an arbitrary number of transmit antennas. STBC uses low-complexity linear processing at the receiver side for detecting the transmitted signals and is capable of achieving the maximum possible diversity gain. Since, the V-BLAST structure is capable of achieving the maximum multiplexing gain, while the STBC scheme attains the maximum antenna diversity gain, it was proposed in [7] to combine the benefits of these two techniques for the sake of providing both antenna diversity as well as spectral efficiency gains. Hence, by combining V-BLAST and STBC, an increased transmit diversity gain can be achieved as compared to the pure V-BLAST scheme, while maintaining a higher spectral efficiency than that of pure STBC. This hybrid scheme was improved in [8] by optimising the decoding order of the different antenna layers. We refer to this layered STBC system as the multi-layer STBC (MLSTBC) arrangement.

MIMO systems require more than one transmit antenna, but satisfying this need may be impractical for shirt-pocket-sized wireless devices, which are typically limited in size and hardware complexity to a single transmit antenna. Furthermore, as most wireless systems support multiple users, user cooperation [9, 10] can be employed, where users support each other by "sharing their antennas" and thus generate a virtual multi-antenna environment. Since the signals transmitted from different users undergo independent fading, spatial diversity can be achieved through the cooperating partners' antennas.

Adaptive modulation and coding techniques that track the time-varying characteristics of wireless channels can be used for significantly increasing the achievable data rate, reliability and spectral efficiency of wireless communication systems [11]. In recent years various Adaptive Coding and Modulation (ACM) assisted schemes have been proposed [12, 13]. The fundamental goal of near-instantaneous adaptation is to ensure that the "most efficient" mode is used in the face of rapidly-fluctuating time-variant channel conditions based on appropriate activation criteria.

Against this state-of-the-art, in this paper we propose two adaptive systems exploiting the combined advantages of user cooperation, the diversity gain of MLSTBC as well as the multiplexing gain of the V-BLAST architecture. The systems assume the formation of a cluster of four users communicating with a common Base Station (BS). The transmission mode of the four cooperating users is adapted by activating four different transmission modes according to the near-instantaneous channel Signal-to-Noise Ratio (SNR) conditions averaged over the four users. In the first system, the total number of users supported is fixed, while the number of users forming a layer in a MLSTBC-like manner is adapted between two and four users per layer. On the other hand, the second system adapts the number of users to be served by activating or deactivating a user (layer) in response to the near-instantaneously fluctuating SNR. In general, the proposed systems transmit using a low-throughput mode, while encountering a low near-instantaneous SNR and use a high throughput transmission mode, when the near-instantaneous SNR is high.

This paper is organised as follows. In Section 2, a brief system

---

†The financial support of Vodafone under the auspices of the Dorothy Hodgkin Postgraduate Award and that of the European Union within the Newcom and Pheonix projects, and the support of EPSRC, UK is gratefully acknowledged.

‡The support provided by KFUPM and the British Council/BAE Summer Research Program to conduct this research is gratefully acknowledged.

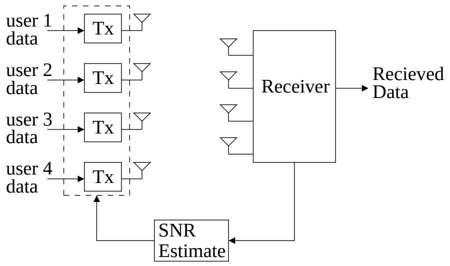

Figure 1: The proposed adaptive system model.

overview is presented, followed by a discussion on the architectural philosophy of the proposed adaptive systems in Section 3. In Section 4, we demonstrate how the proposed system performs and finally we conclude in Section 5.

2. SYSTEM OVERVIEW

The system we consider is a cellular system employing user cooperation. Cooperation starts by forming clusters of users, where the users within a cluster cooperate by transmitting data to a common BS, in order to achieve a diversity gain. The specific assignment of users to a given cluster is based on the quality of the Inter-User Channels (IUC), where we assume that the IUC quality is statistically speaking better than the individual uplink quality. This is a reasonably practical assumption, since users within a cluster are located closer to each other than to their serving BS. In this contribution, we focus our attention on characterising the performance of a single established cluster, without being concerned about the protocols used for setting up a cluster. Moreover, for the sake of supporting the exchange of data amongst the cooperating users, we assume a Time Division Duplexing (TDD) system where users share their data amongst each other on different time slots before communicating with the BS. Furthermore, we assume perfect synchronisation between the transmitting users. This assumption becomes reasonably accurate when the distances between the users of a cluster are small compared to the distance separating the users from the BS, provided that the users have been instructed by the BS to advance their transmission instants according to their propagation delays, i.e. distances, so that their signals arrive at the BS quasi-synchronously[1]. Moreover, we consider transmissions over a correlated narrowband Rayleigh fading channel, associated with a normalised Doppler frequency of $f_D = f_d T_s = 0.01$, where f_d is the Doppler frequency and T_s is the symbol duration. The complex Additive White Gaussian Noise (AWGN) that contaminates the received signals is a zero-mean complex Gaussian random variable having a variance of $N_0/2$ per dimension, with $N_0/2$ representing the double-sided noise power spectral density expressed in W/Hz.

We assume a TDD system, where the correlation between the fading envelope of the UpLink (UL) and the DownLink (DL) is high, since the UL and the DL slots are transmitted at the same frequency and at a low TDD time-slot displacement, hence they are likely to fade coincidentally in low-Doppler pedestrian scenarios, unless frequency-selective fading is encountered owing to the high-rate transmissions. Therefore, when transmitting a frame, the BS estimates the SNR of the receivers at the other end of the link based on the SNR estimate at the BS and selects the most appropriate transmission mode accordingly.

3. ADAPTIVE SYSTEM

In the section we propose two adaptive cooperative diversity aided systems. The proposed adaptive systems are designed to serve a cluster of four users communicating with a common BS, where each of the users has a single transmit antenna, whereas the BS has four receive antennas. A high-level block diagram of the proposed system is shown in Figure 1. It is worth noting that the proposed schemes can be readily generalised to any number of users. We assume that a suitable transmission mode of the four users within a cluster is selected according to the near-instantaneous channel conditions of the four users, which is quantified in terms of their average SNR.

As shown in Figure 1, each user transmits his/her data activating a specific mode of operation, depending on the near-instantaneous channel conditions. Each user's data is received by the BS as well as by the other users in the cluster, which can be exploited later by the Mobile Stations (MS) for cooperation using the detect-and-forward strategy [9]. At the BS side, the receiver applies the appropriate decoding process according to the specific transmission scheme employed and estimates the near-instantaneous SNR averaged over the users within a cluster to decide on the transmission scheme for the next transmission frame or packet.

The main objective of introducing the proposed systems is to maximise the achievable system throughput, while maintaining a specified target BER performance that guarantees a certain quality-of-service level. More specifically, in this treatise we aim for maintaining a target BER of 10^{-3}, while transmitting data at the highest possible effective throughput at the near-instantaneous SNR experienced by the transmitted data frame.

The first proposed system, referred to as System 1, attempts to maximise the achievable throughput of *each individual user* by varying the transmission configuration of the four users. Specifically, a virtual single-layer STBC configuration is used in the lowest-throughput mode while a virtual two-layer MLSTBC scheme is formed in the highest-throughput mode in conjunction with different modulation schemes. The single-layer STBC mode is formed by allowing the four users in the cluster to detect-and-forward the data received from their partners, in order to form a four-antenna STBC. The same principle is used in the case of MLSTBC, with the basic difference that a pair of users form a virtual two-antenna based STBC scheme, where these two STBCs are essentially used as a two-layer V-BLAST system. In order to be able to use MLSTBC-like systems, each cooperating user has to share his/her data with the other three cooperating users before transmission. Again, the system employs TDD for exchanging the data between the different users. That is, each user is assigned a time slot for broadcasting his/her data to the other cooperating users in the same layer, before communicating with the BS. For example, when the four users implement a virtual four-antenna aided STBC system, the system needs four time slots for the four users to communicate their data amongst each other for cooperation. This results in a further potential delay in the UL communication with the BS. This is not a crucial problem, when slow shadow fading or slow signal-to-interference plus noise (SINR) fluctuations are encountered. However the problem becomes more serious, when these impairment fluctuate rapidly. This problem can be dealt with by incorporating long-range channel estimation [14] and prediction, where the BS predicts the UL channel quality for specifying the UL mode of operation in that specific time slot.

On the other hand, the second proposed system, referred to as System 2, attempts to maximise the achievable throughput of the *entire cluster of four users* by adapting the transmission configuration of the users. The system commences its operation in a four-layer V-BLAST-like transmission configuration supporting all of the four users within the cluster. If the near-instantaneous SNR averaged over the four users drops below a certain threshold, the cluster has to be reconfigured in a more robust but lower-throughput mode by dropping a user to form a virtual three-layer V-BLAST system, while providing the user just dropped from the cluster with a dedicated channel. If the near-instantaneous SNR

---

[1] In the currently operational cellular systems, this procedure takes place during the call-set-up phase and it is then regularly updated using adaptive timing advance control.

averaged over the remaining three users drops further below a certain threshold, the cluster drops another user and the BS provides this user with a dedicated channel for his/her communication. This process is continued, until each user has his/her own dedicated channel in the lowest-throughput mode. On the other hand, as the near-instantaneous SNR increases, the system incorporates an additional cooperating user in the cluster. The user added to the cluster is the one who had the highest near-instantaneous UL SNR in his/her dedicated channel. This system does not require any exchange of data between the cooperating users, since the users are cooperating to share the system resources such as the carrier frequency and the bandwidth, rather than for the sake of achieving an additional diversity or multiplexing gain. The system activates and deactivates users in the cluster according to the near-instantaneous received SNR. As the number of users cooperating in a cluster decreases, the level of interference at the receiver side decreases and this results in a better performance. Again, the transmission regime of the cluster is adapted for the sake of maximising the total throughput, while maintaining a target BER of 10^{-3}.

3.1. V-BLAST

V-BLAST, as mentioned previously, provides a high throughput in exchange for a low diversity gain. Let $\mathbf{x}^T = [x_1 \quad x_2 \quad x_3 \quad x_4]$ denotes the vector of symbols to be transmitted by the four users during a symbol interval. Then the corresponding vector of the received signal can be represented as

$$\mathbf{r}_t = \mathbf{H} \cdot \mathbf{x}_t + \mathbf{n}_t, \tag{1}$$

where $\mathbf{r}_t$ represents the vector of received signal at the BS, $\mathbf{H}$ is an $(n_r \times n_t)$ matrix where n_t is the number of users transmitting simultaneously, n_r is the number of receive antennas at the BS and h_{ij} represents the channel coefficient between user j and the BS antenna i, while $\mathbf{n_t}$ denotes the noise vector at time instance t.

V-BLAST detection is carried out using SIC and the zero forcing (ZF) algorithm [4].

3.2. Four-Antenna STBC

STBC has the potential of achieving the maximum transmit diversity order specified by the number of transmit antennas n_t as well as the number of receive antennas n_r, while using maximum-likelihood decoding based on linear processing of the received signals. Again, in this paper we use two different four-antenna based STBC systems for transmitting the data from the four cooperating users forming a cluster. The first STBC, denoted as $G4$ [6, 15], has a low effective rate of $R = 1/2$ and a better BER performance compared to the $H4$ STBC scheme [6, 15], which has a rate of $R = 3/4$. Thus the lower-throughput system can be used, when the near-instantaneous SNR is low and as the SNR increases, the higher-throughput but lower-diversity-gain system can be employed.

The $G4$ and $H4$ STBC schemes can be described by their transmission matrices as in [15, p.404], where each column corresponds to the data transmitted by each user within a given symbol duration [6, 15].

3.3. Multi-Layer STBC

The MLSTBC arrangement constitutes a tradeoff between the high-diversity STBC and the high-throughput V-BLAST schemes. In the following, we describe the encoding and decoding processes of the MLSTBC arrangement, with a focus on using four transmit and four receive antennas. In the MLSTBC system we consider the four transmitters grouped into two layers, where each layer is composed of two antennas.

In each cooperating cluster, each block of $2B$ bits is encoded by a component STBC in the dedicated TDD time slot. The encoding process is similar to that of Alamouti's STBC in [5]. However, at the receiver side, a specific STBC imposes interference on the other layer. Hence, before decoding the data using the STBC maximum likelihood decoder [5], we have to suppress the interference using the successive group interference cancellation scheme of [7].

The received data can be modelled as in (1). Let $\mathbf{H}_1$ and $\mathbf{H}_2$ denote the specific versions of the matrix $\mathbf{H}$ generated after setting the particular columns corresponding to layers two and one, respectively, to zero. Then, $\mathbf{r}_t$ can be represented as

$$\mathbf{r}_t = \mathbf{H}_1 \cdot \mathbf{x}_t + \mathbf{H}_2 \cdot \mathbf{x}_t + \mathbf{n}_t. \tag{2}$$

The more beneficial decoding order of the two layers is determined on the basis of detecting the higher-power layer first for the sake of a higher correct detection probability. For simplicity, we assume that layer 1 is detected first which allows us to eliminate the interference caused by the signal of layer 2. For this reason, the decoder of layer 1 has to compute a matrix $\mathbf{W}$, so that we have $\mathbf{W} \cdot \mathbf{H}_2 = 0$. Therefore, the decoder computes an orthonormal basis for the left null space of $\mathbf{H}_2$ and assigns the vectors of the basis to the rows of $\mathbf{W}$. Multiplying $\mathbf{W}$ by $\mathbf{r}_t$ suppresses the interference of layer 2 originally imposed on layer 1 and generates the following signal:

$$\widehat{\mathbf{r}}_\mathbf{t} = \mathbf{W} \cdot \mathbf{r}_t = \mathbf{W} \cdot \mathbf{H}_1 \cdot \mathbf{x}_t + \underline{0} + \mathbf{W} \cdot \mathbf{n}_t = \widehat{\mathbf{H}} \cdot \mathbf{x}_t + \widehat{\mathbf{n}}_t. \tag{3}$$

Following these operations, according to Equation (3) the decoder applies maximum likelihood STBC decoding for recovering the transmitted signals of the first layer corresponding to the first and second users. Then, the decoder subtracts the remodulated contribution of the decoded symbols of layer 1 from the composite twin-layer received signal. Finally, the decoder applies direct STBC decoding to the second layer, since the interference imposed by the first layer has been eliminated.

The first decoded layer has a diversity order of (2×4), while the second layer has an order of (4×4). In order to determine the more meritorious decoding order, the decoder processes the specific layer having the higher post-detection SNR, which is directly proportional to the norm of $\widehat{\mathbf{H}}$. Thus, to determine the more beneficial decoding order, the decoder computes the orthonormal basis for the left null space of both $\mathbf{H}_1$ as well as $\mathbf{H}_2$ and then evaluates the norm of the corresponding matrix $\widehat{\mathbf{H}}$ and decodes the specific layer having the higher norm first.

The above procedure can be extended to an arbitrary number of transmit and receive antennas as well as to any number of V-BLAST layers, where the successive group interference cancellation is carried out iteratively.

3.4. Adaptation Schemes

STBC has the potential of providing a high diversity gain at the cost of having a relatively low throughput. By contrast, MLSTBC is capable of providing a higher throughput, at the cost of a higher SNR requirement. Therefore, in order to maximise the achievable system throughput, the system was configured to switch between different-throughput and different-robustness modes, in order to maximise the effective throughput, while maintaining a given target BER performance. A low-throughput high-diversity-gain mode can be activated by the system, when the near-instantaneous SNR is initially low but gradually increases, higher-throughput lower-diversity-gain modes can be activated, while always satisfying the target BER.

As mentioned in Section 1, in this contribution we consider two different adaptive systems that result in a different throughput, while maintaining the target BER of 10^{-3}. Again, the proposed adaptive systems assume the formation of a cooperative cluster of four users, each having a single transmitter, while communicating with a BS employing four receive antennas.

The system parameters of the first proposed adaptive system, namely System 1, are listed in Table 1. The system adapts the transmission scheme between the lowest-throughput single-layer $G4$ STBC mode activated at low SNRs, switching to the highest-throughput twin-layer MLSTBC mode activated at high SNRs. The attainable system throughput varies between 1 BPS and 8 BPS as follows. At low near-instantaneous SNRs, the low-throughput

Table 1: System parameters for system 1

No. of users per cluster	4
No. of Rx Antennas	4
Mode 1	G4 STBC, QPSK Throughput=1 BPS
Mode 2	H4 STBC, QPSK Throughput=1.5 BPS
Mode 3	Two Layers MLSTBC, QPSK Throughput=4 BPS
Mode 4	Two Layers MLSTBC, 16 QAM Throughput=8 BPS

Table 2: System parameters for system 2

No. of users per cluster	4
No. of Rx Antennas	4
Mode 1	one user Throughput=2 BPS
Mode 2	Two users Throughput=4 BPS
Mode 3	Three users Throughput=6 BPS
Mode 4	Four users Throughput=8 BPS

high-diversity G_4 STBC mode can be employed and as the near-instantaneous SNR increases, the higher throughput H_4 STBC mode can be activated. Further increase in the near-instantaneous SNR results in the activation of the MLSTBC system employing two virtual V-BLAST layers of two users each, while using QPSK modulation. Finally, the highest-throughput mode is constituted by the MLSTBC mode employing two layers of two users each, while employing 16 QAM transmission [1].

The parameters of the second adaptive system, namely System 2, are listed in Table 2. In this system, the V-BLAST ZF receiver is employed all the time, while the number of cooperating users is adapted. A cluster of four users is formed. As the near-instantaneous SNR decreases, the specific user having the lowest near-instantaneous SNR is dropped out of the cooperating cluster and is assigned a different independent non-cooperative channel by the BS in order to transmit his/her data. As the number of users decreases, the inter-user interference is reduced and thus the system's performance improves. As the SNR decreases further, more users are removed from the cooperating cluster, until we are left with four users communicating over four independent channels. On the other hand, as the SNR and SINR increases, the BS may incorporate further users in the cooperating cluster, namely the specific users benefiting from having the channel exhibiting the highest near-instantaneous SNR.

4. RESULTS AND DISCUSSIONS

We consider a system employing a cluster of four users communicating with a BS employing four antennas, in order to demonstrate the performance improvements achieved by the proposed systems. All simulation parameters of System 1 and System 2 are listed in Tables 1 and 2 which were configured for maintaining a target BER of 10^{-3}.

Figure 2 shows the BER as well as the effective system throughput of System 1. The BER curve of the adaptive system, which can be viewed by referring to the y-axis on the left of the figure, is plotted along with those of the individual modes of operation. The BER performance reaches the target BER around SNR=1.75 dB and then it never exceeds the target BER for the SNRs considered, while switching between the different transmission modes of Table 1. The y-axis at the right of Figure 2 quantifies the achievable effective throughput of System 1. Depending on the channel quality quantified in terms of the channel SNR, the transmitter activates one of the transmission modes outlined in Table 1. The effective throughput of the system varies from 1 BPS recorded for the minimum-throughput mode to 8 BPS encountered for the highest-throughput mode. For example, if we calculate the throughput of Mode 1, employing $G4$ in conjunction with QPSK yields $2 \cdot 1/2 = 1$ BPS. Figure 3 portrays the mode selection probability histogram of System 1. It is clear from the figure that as the average SNR increases, the higher-throughput modes are activated more often.

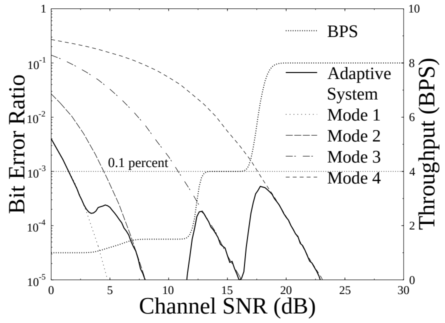

Figure 2: BER and BPS throughput performance of System 1 for a target BER of 10^{-3} with perfect IUC.

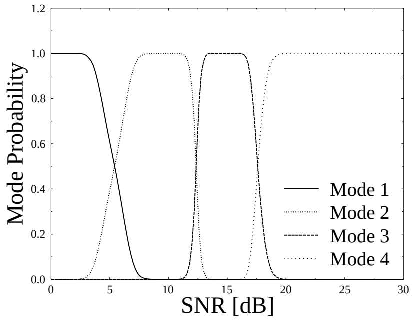

Figure 3: Mode selection probability histogram of System 1 for a target BER of 10^{-3} with perfect IUC.

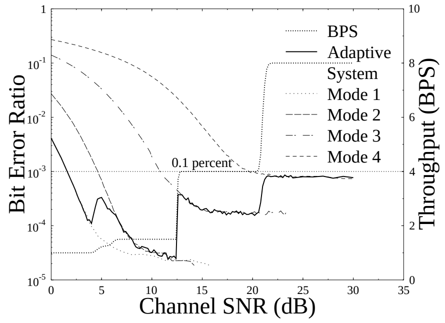

Figure 4: BER and BPS throughput performance of System 1 for a target BER of 10^{-3} with IUC SNR= 30 dB.

As mentioned previously, the IUC quality has a substantial effect on the achievable performance of the systems benefiting from cooperation. In other words, if the link between the cooperating users exhibits a low quality, then the advantages of employing user cooperation erode. Therefore, we include Figure 4, in order to demonstrate how System 1 performs when the IUC reaches SNR=30 dB. The system considered assumes the formation of a cluster of four users, where the inter-user distance is significantly lower than that between the users and the BS. Therefore, it is feasible to assume an IUC SNR of 30 dB. As shown in Figure 4, the BER reaches the target BER performance of 10^{-3} at the same SNR as in Figure 2, where having a perfect IUC was assumed. For SNRs in excess of this value the system's performance remains

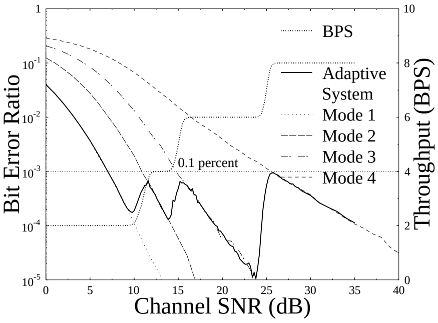

Figure 5: BER and BPS throughput performance of System 2 for a target BER of 10^{-3} with perfect IUC.

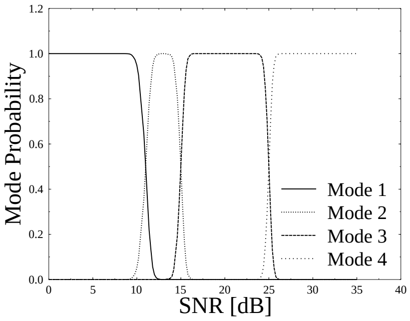

Figure 6: Mode selection probability histogram of System 2 for a target BER of 10^{-3} with perfect IUC.

below the target BER for all the SNRs considered. On the other hand, the effective throughput of the system assuming a perfect IUC becomes better than that assuming an IUC SNR of 30 dB. A comparison between Figures 2 and 4 demonstrates that the difference observed is mainly in the range between 15 dB and 20 dB, while the associated BPS throughput is almost the same for all other SNRs.

Figure 5 shows the BER as well as the effective system throughput performance of System 2. The BER curve of the adaptive system, which can be viewed by referring to the y-axis on the left of the figure, is plotted along with those of the individual modes of operation. The BER performance reaches the target BER around SNR$=$ 7 dB and then remains below the target BER for all the SNRs considered, while switching between the different transmission modes. The y-axis at the right of Figure 5 quantifies the achievable effective throughput of System 2. Depending on the channel quality quantified in terms of the channel SNR, the transmitter activates one of the four transmission modes outlined in Table 2. The effective system throughput varies from 2 BPS for the minimum-throughput mode to 8 BPS for the highest-throughput mode. For example, if we calculate the throughput of Mode 1 characterised in Table 2, supporting a single user employing QPSK, yields 2 BPS. An important point concerning this system is that the individual users' throughput does not vary, while the total cluster's throughput does change. However, as the SNR decreases, the BS removes a user from the cooperating cluster, who will communicate with the BS using an independent dedicated channel and thus the overall system requires more resources, such as an additional TDD time slot. Therefore, System 2 maintains the target BER, while increasing the achievable system throughput and minimising the resources required. Figure 6 portrays the mode selection probability of System 2. It is clear from the figure that as the average SNR increases, the higher-throughput modes are activated more often.

5. CONCLUSION

In this paper we proposed two adaptive systems which amalgamate the advantages of cooperative diversity, STBC as well as V-BLAST, while near-instantaneously adapting the system configuration for the sake of achieving the highest possible throughput, as well as maintaining a given target BER. System 1 benefits from a higher diversity gain with the aid of MLSTBC and thus attains the target BER of 10^{-3} at an SNR as low as 1.75 dB. The throughput of this system varies between 1 BPS and 8 BPS. By contrast, System 2 benefits from the higher multiplexing gain of V-BLAST and thus has an effective throughput varying between 2 BPS and 8 BPS. Our future research will consider the mathematical performance analysis of the two proposed systems, in addition to the design of an optimised adaptive scheme, where adaptation will be based on the more reliable channel quality metric of the estimated BER value of the received frames' rather than on the less reliable channel SNR metric.

6. REFERENCES

[1] L. Hanzo, S. X. Ng, T. Keller, and W. Webb, *Qaudrature Amplitude Modulation: From Basics to Adaptive Trellis-Coded, Turbo Equalised and Space-Time Coded OFDM, CDMA and MC-CDMA Systems, 2nd Edition*. Chichester, England: John Wiley and Sons Ltd and IEEE Press, 2004.

[2] G. Foschini and M. Gans, “On Limits of Wireless Communication in a Fading Environment when using Multiple Antennas,” *Wireless Personal Comunications*, vol. 10, pp. 311–335, Mar. 1998.

[3] E. Telatar, “Capacity of Multi-Antenna Gaussian Channels,” *European Transactions on Telecommunications*, vol. 10, pp. 585–595, Nov./Dec. 1999.

[4] P. Wolniansky, G. Foschini, G. Golden, and R. Valenzuela, “V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel,” in *International Symposium on Signals, Systems, and Electronics*, (Pisa), pp. 295–300, September 1998.

[5] S. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[6] V. Tarokh, H. Jafarkhani, and A. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[7] V. Tarokh, A. Naguib, N. Seshadri, and A. Calderbank, “Combined array processing and space-time coding,” *IEEE Transactions on Information Theory*, vol. 45, no. 4, pp. 1121–1128, 1999.

[8] M. Tao and R. Cheng, “Generalized layered space-time codes for high data rate wireless communications,” *IEEE Transactions on Wireless Communications*, vol. 3, no. 4, pp. 1067–1075, 2004.

[9] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity. Part I. System description,” *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, 2003.

[10] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity. Part II. Implementation aspects and performance analysis,” *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, 2003.

[11] L. Hanzo, C. Wong, and M. Yee, *Adaptive wireless transceivers: turbo-coded, turbo-equalized and space-time coded TDMA, CDMA, and OFDM systems*. Chichester, UK: John Wiley and Sons, 2002.

[12] W. Webb and R. Steele, “Variable rate QAM for mobile radio,” *IEEE Transactions on Communications*, vol. 43, no. 7, pp. 2223–2230, 1995.

[13] A. Goldsmith and S.-G. Chua, “Variable-rate variable-power MQAM for fading channels,” *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, 1997.

[14] L. Hanzo, M. Mnster, B. Choi, and T. Keller, *OFDM and MC-CDMA for broadband multi-user communications, WLANs and broadcasting*. Chichester, UK: Wiley, 2003.

[15] L. Hanzo, T. H. Liew, and B. L. Yeap, *Turbo coding, turbo equalisation and space time coding : for transmission over fading channels*. Chichester, UK: Wiley: IEEE Press, 2002.