Wireless Cooperative Communication

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Seminar report by
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1 Introduction

One of the crucial challenge in mobile wireless communication is the substantial variation in signal strength due to multipath propagation. As a result we will have a fading channel which will degrade the performance of the communication system severely. One coping mechanism to avert the problem of fading in the channel is to utilize the diversity that can be provided by two statistically independent channel paths as shown in figure 1.

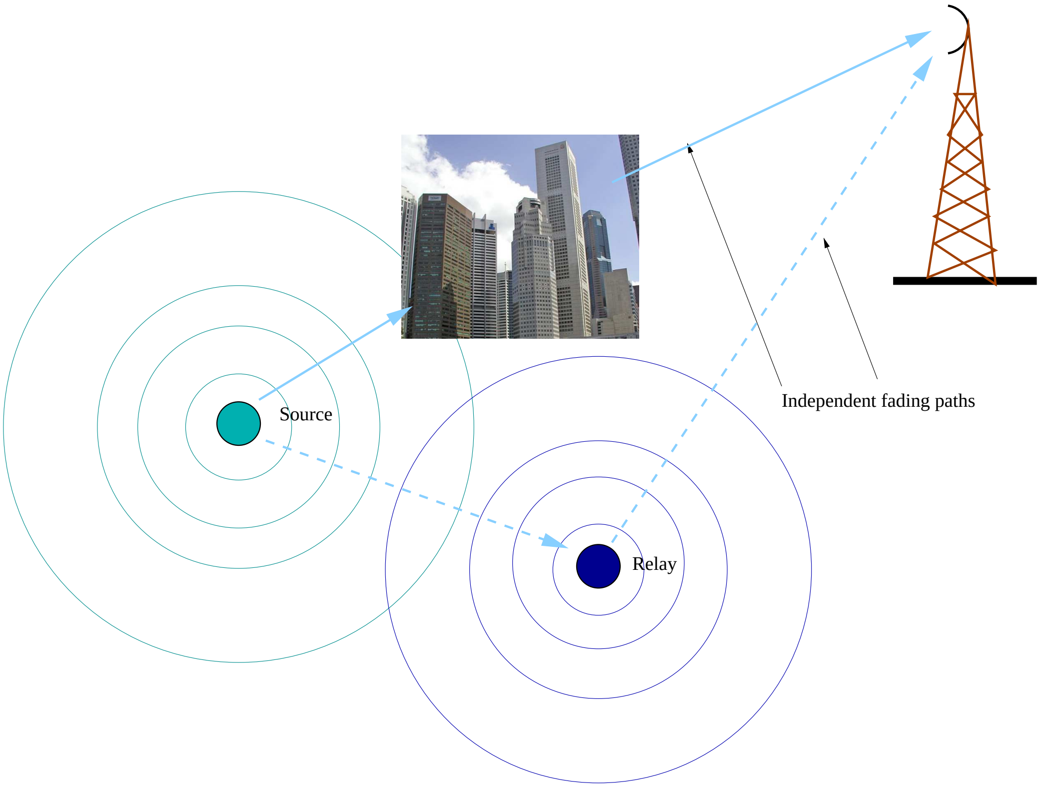

Figure 1: Cooperative communication

This can either be performed by sending two independent copies of the same signal or deploy multiple antenna for transmit diversity. The latter case may not be straight forward to implement it on wireless devices where they are limited by size or hardware complexity to one antenna. On the other hand we can utilize the property of omnidirectionalty of the wireless antennas; signals transmitted to the destination can be overheard by the partner. Cooperative communication is thus a new paradigm that enables single antenna wireless devices to communicate cooperatively and thereby creating virtual multiple input multiple output (MIMO) system and generate diversity. In this report some of the approaches of wireless cooperative communication developed in the recent years will be summarized.

Section 2 presents briefly about a three node relay channel investigated by Cover and El Gamal [2] which reveals the basic concept on cooperative communication. In section 3 amplify-and-forward which is one of the simple cooperative signaling will be presented. In section 4 detect and forward and in section 5 coded cooperation which is a method that integrates cooperation into channel coding will be presented. In section 6 some results explored from the literature will be presented and discussed. In section 7 and 8 open issues and conclusion remarks are presented.

2 Relay channel

The basic ideas of cooperative communication can be traced back to the work of [5, 2] on information theoretic properties of relay channel. The later treat certain discrete memoryless and additive white Gaussian noise relay channels. In this work lower bounds on capacity, i.e., achievable rates, were established via different random coding schemes depending on the role of the relay to actively help the source. Relay channels and their extensions form the basis for the study of cooperative diversity because relaying and cooperative diversity essentially create virtual antenna array. The capacity analysis for AWGN degraded relay channel of three-node network, shown in figure 2. is provided by Cover and El Gamal [2]

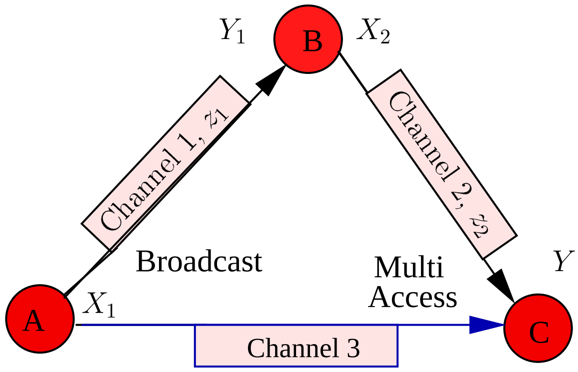

Figure 2: The relay channel

The transmitter X_1 is assumed to have power P_1 and the relay transmitter is assumed to have power P_2. The relay node Y_1 receives $X_1 + z_1$, where z_1 is additive noise with variance σ_1. The destination receiver Y receives the sum of the relay signal X_2 and a corrupted version of Y_1, i.e, $Y = X_2 + Y_1 + z_2$, where z_2 is additive noise with variance σ_2. In [2], the variance of additive noise for the third path is not explicitly shown, and thus it can be interpreted as $z_3 = z_1 + z_2$ and it is assumed that the relay signal X_2 is not corrupted by noise. The question addressed ultimately is how X_2 use the its knowledge of X_1 obtained through Y_1 to help Y understand X_1. The capacity of such relay channel is computed in [2].

$$C^* = \max_{0 \leq \alpha \leq 1} \min\{C(\frac{P_1 + P_2 + 2\sqrt{\overline{\alpha} P_1 P_2}}{N_1 + N_2}), C(\frac{\alpha P_1}{N_1})\} \tag{1}$$

where $\overline{\alpha} = 1 - \alpha$ and $C(x) = \frac{1}{2}\log(1 + x)$.

A channel is classified as degraded relay channel if the following probability holds. $p(y, y1 \setminus x1, x2) = p(y1 \setminus x1, x2)p(y \setminus y1, x2)$. Equivalently a relay channel is degraded if $p(y \setminus y1, x1, x2) = p(y \setminus y1, x2)$. We have degraded relay channel when the relay y_1 is better than y and reverse degraded channel if relay y_1 is worse than y.

The direct contribution of the above relay channel study towards the cooperative communication is for the situation when the relay fully decodes the source message. C* is achieved if Y_1 discovers X_1 perfectly , then X_1 and X2 cooperate coherently in the next block to resolve the remaining Y_2 uncertainty about X_1. However in this scheme it should be remembered that the relay's sole purpose is to assist the main channel.

3 Amplify-And-Forward

Amplify-and-forward, as the name suggests, is a simple cooperative signaling where each user overhears the noisy version of signal transmitted by its partner and then retransmits after amplification. This method was proposed in [4]. It is assumed that the path from the cooperating partner to the destination and the path from the source to the destination/basestation is statistically independent and at high SNR between the relay and the source, full diversity of order two can be archieved. However, as shown in figure 4, the maximum multiplexing gain that can be achieved is that of the point to point link. Decision about the transmitted bit is made at the base station from the combined information and for optimal decoding the channel coefficients in the two paths in figure 3. is assumed to be known at the base station. To avail the channel coefficients at the basestation some feedback line is required for estimating and updating the coefficients.

$$\begin{bmatrix} Y_{0,BC} \\ Y_{0,MA} \end{bmatrix} = \begin{bmatrix} h_{10} \\ h_{12}\beta h_{20} \end{bmatrix} X_1 + \begin{bmatrix} 0 & 1 & 0 \\ h_{20}\beta & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_0 \\ Z_0 \end{bmatrix} \tag{2}$$

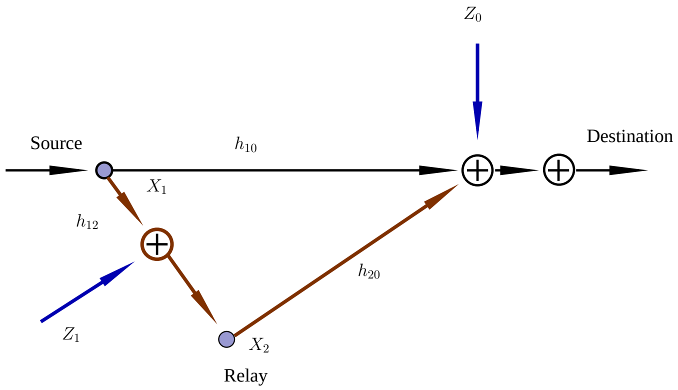

Figure 3: Amplify-and-Forward [Laneman et al.]

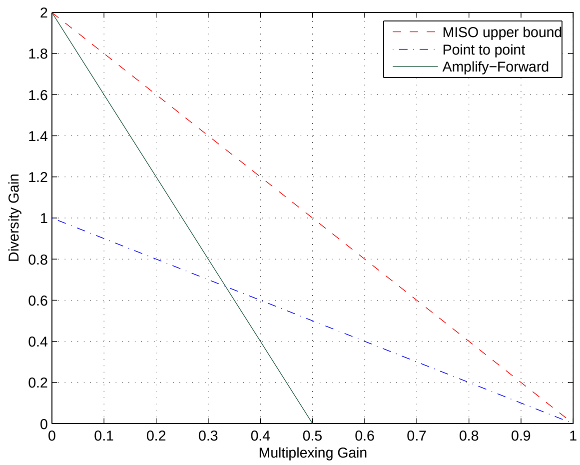

Figure 4: Diversity vs. Multiplexing (Laneman et al.)

4 Detect-And-Forward

In this kind of cooperative communication the partner tries to detect the message from the source and retransmits the detected bit to the basestation. Akin to the situation in the previous section, the partner provides a second data path enriching diversity. In [3] CDMA implementation for two users case is investigated. Here two users are paired to cooperate with each other. The coherence time of the channel is L symbol period, and for the specific implementation in [3] $L = 3$. The user's codes are assumed orthogonal.

$$X_1(t) = a_1 b_1^{(1)} c_1(t), a_1 b_1^{(2)} c_1(t), a_1 b_1^{(3)} c_1(t) \tag{3}$$

$$X_2(t) = \underbrace{a_2 b_2^{(1)} c_2(t)}_{\text{Period 1}}, \underbrace{a_2 b_2^{(2)} c_2(t)}_{\text{Period 2}}, \underbrace{a_2 b_2^{(3)} c_2(t)}_{\text{Period 3}} \tag{4}$$

where $a_j = \sqrt{P_j/T_s}$, P_j is user j's power and T_S is symbol period. $\widehat{b}_j^{(i)}$ is estimate of j's i^{th} bit. The above equations show the signaling format when there is no cooperation. Let's consider now X_1 and X_2 are being partnerd for cooperation, and the signaling format is as shown bellow.

$$\begin{aligned} X_1(t) =& [a_{11} b_1^{(1)} c_1(t), a_{12} b_1^{(2)} c_1(t), \\ & a_{13} b_1^{(2)} c_1(t) + a_{14} \widehat{b}_2^{(2)} c_2(t)] \end{aligned} \tag{5}$$

$$\begin{aligned} X_2(t) =& \underbrace{[a_{21} b_2^{(1)} c_2(t)}_{\text{Period 1}}, \underbrace{a_{22} b_2^{(2)} c_2(t)}_{\text{Period 2}}, \\ & \underbrace{a_{23} b_2^{(2)} c_2(t) + a_{24} \widehat{b}_1^{(2)} c_1(t)]}_{\text{Period 3}} \end{aligned} \tag{6}$$

Here the (a_{ij}) coefficients represent to the power allocation to the different portion of the message to be sent from the cooperating partners. The (a_{ij})

coefficients also control how much power is allocated to a user's own bits versus the bits of the partner, while maintaining the average power constraint of P_j for user j over L periods. Here it should be emphasized that the average power allocation is required to be maintained. One interesting factor of this scheme is the level of cooperation can be varied based on the interuser channel quality. More power can be allocated for cooperation when interuser channel is favorable and viceversa if not.

In the first and second interval each user transmits its own bits. Each user then detects (estimates) the other's second bit and in the third interval both users transmit a linear combination of their own second bit and the partner's second bit.

One good advantage of this scheme is simplicity and adaptability of the scheme to channel conditions. Where as in the amplify and forward scheme there is a possibility also to amplify and retransmit the noise. Evidently, the disadvantage of this scheme is the possibility that detection by the partner might not be successful and thus the method fails in case of unsuccessful detection. To avoid such problem in [1] a hybrid decode-and-forward scheme is proposed. Which is a cooperative mode for low inst. SNR or bad fading channel and non cooperative mode for high inst. SNR. There is also a good arguable point for the users reduced data rate that is sending two new bits per three symbols. This point is investigated in detail in [3] and the conclusive result is that an overall throughput gain is achieved. The data rate vs throughput dispute can be settled by the illustrative phrase in [3] "It may better be better to receive, say, 1 very high SNR bit per symbol period, than to receive, say, 10 very low SNR bit per symbol period". This point is also supported by the following equation and the corresponding plot in figure 5.

$$\eta = (1-\upsilon)C_{\text{BSC}}(Q(\sqrt{\frac{\text{SNR}_0}{1-\upsilon}})) \tag{7}$$

where $C_{BSC}(p)$ is the binary symmetric channel with crossover probability of p. The transmitters employ BPSK and do no transmit during a fraction of υ of its L symbol period. SNR_0 is the nominal SNR that would be in effect if the transmitter were transmitting during all the symbol periods. As can be inferred from the plots, there is negligible loss of throughput at low SNR_0. The design trade of will be to optimize between the non cooperative L vs. L_c. The optimization problem can be stated as the loss incurred by allocation of some period for cooperation shouldn't outweigh the throughput gain due to coopeation, thus L_c doesn't have to be constant all the time.

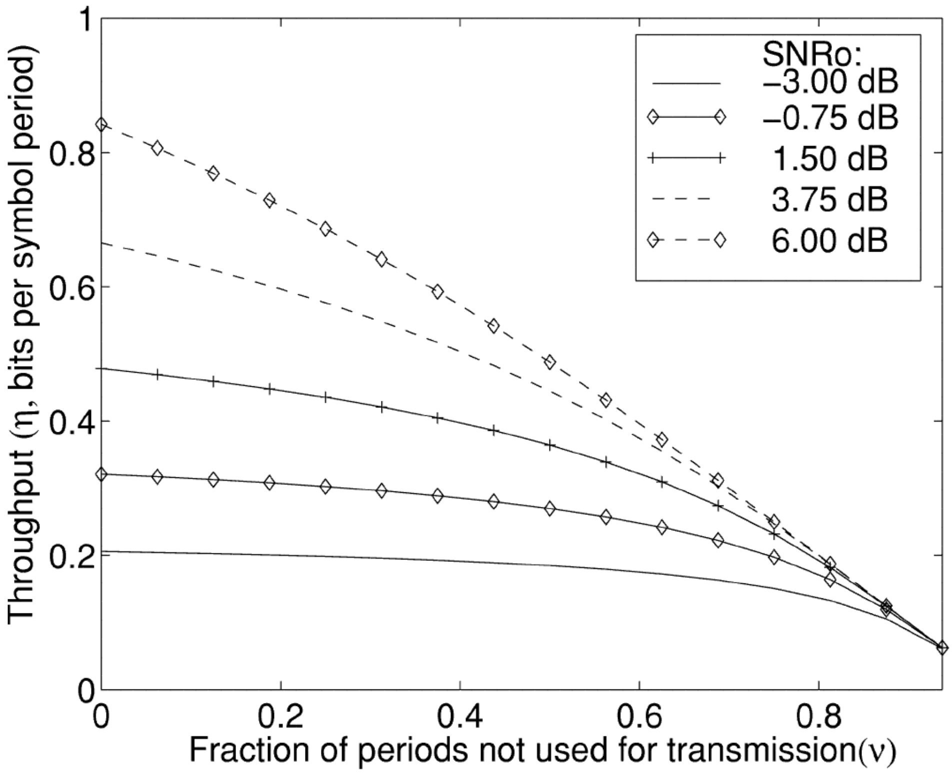

Figure 5: Throughput vs. unused symbol periods

5 Coded Cooperation

Coded cooperation is a method that integrates cooperation into channel coding [1]. Here different portions of each user's (partners) code word are sent via independent fading path similar to the other cooperative schemes. Then each user tries to transmit incremental redundancy to its partner.

let's assume that the original codeword has $N_1 + N_2$ bits (**puncturing**) for each user. The divided source data blocks are augmented by cyclic redundancy check **CRC**. The first partition is a valid codeword with N_1 bits and also the remaining N_2 bits are the puncture bits which are also weaker codeword on its own. Partitioning of the original message block via other means is also possible. In the first frame each user sends N_1 bits or the first codeword and in the second frame partner's 2^{nd} code partition is transmitted. The level of cooperation is denoted as N_2/N. For unsuccessful decoding of partners second code partition, user transmits its own second partition. The key to the efficiency of coded cooperation is that all this is managed automatically through code design with no feedback between the users. Figure 6. depicts the situation considered in [3].
In the second frame of transmission, users act independently with no knowledge of whether their own first frame was correctly decoded or not. Here four possible scenario might arise; both users cooperate, user 1 cooperate and user 2 doesn't, user 2 cooperate and user 1 doesn't, both users don't cooperate. The performance plots obtained by [3], shown in figure 7. embeds all the four possibilities of cooperation.

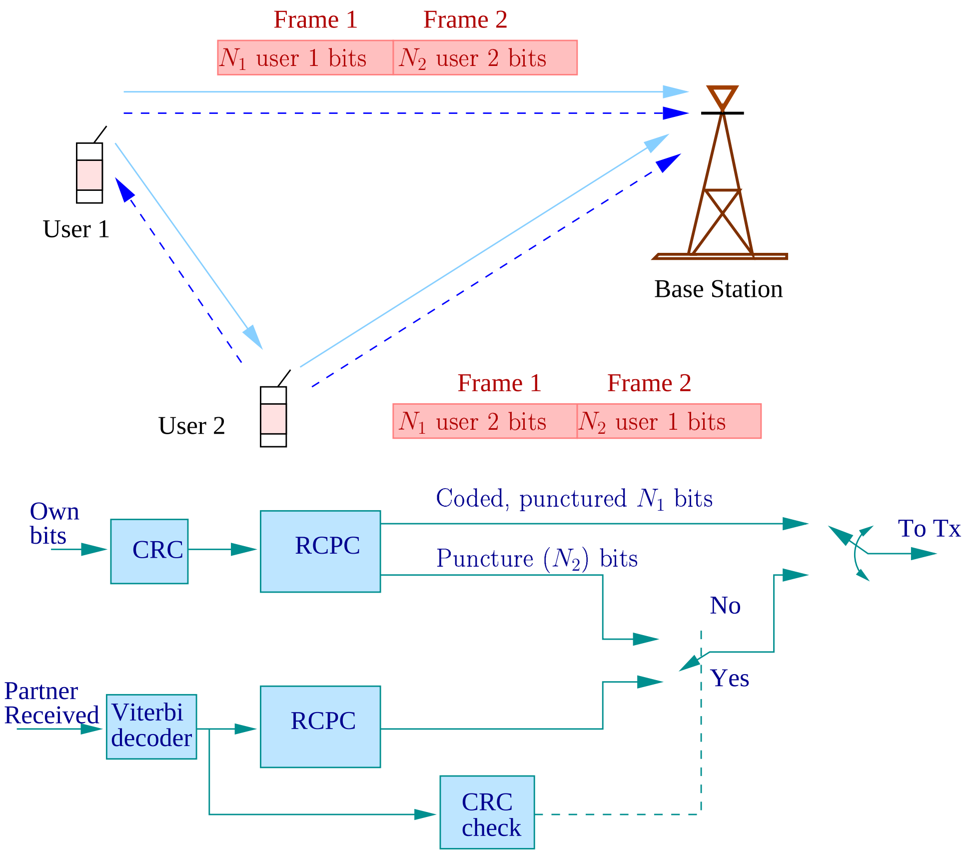

Figure 6: Coded Cooperation [Nosratinia et al.]

6 Results and Discussion

Here the the results obtained by [3] for all the cooperative schemes discussed above is summarized. For reasonable comparison, the base line system is kept to have overall rate 1/4 code rate. For both cases of hybrid and decode-and-forward, and amplify and forward, a rate compatible punctured code (RCPC) rate 1/2 is used. This codeword is repeated by the relay to have overall code rate 1/4. In the case of coded cooperation again to be consistent N_2/N is required to be 1/4 which is thus 25% level of cooperation. To obtain this, the two users transmit a code word punctured to 1/3 in the first frame.

In the second frame the relay transmits the bits punctured from the first frame such that the total bits received for each user form a rate 1/4 code word.

The interuser channel is 10dB SNR bellow the uplink channel. Figure 7. is the performance plots obtained by [3]. Clearly we see that the diversity improves markedly over the comparable non cooperative system. The diversity is the slope of the block error rate vs. SNR curves at high SNR which is two in this case for cooperation. This diversity level is equivalent to the diversity provided by standard two-antenna transmit like Alamouti's scheme or receive diversity schemes. One important observation is also the the robustness of cooperative communication to the conditions of the interuser channel. There is substantial error rate improvement even when the interuser channel quality is poorer than that of the uplink channels.

7 Challenges

As discussed in the previous sections, given the availability of on the shelf solutions for some challenges, it is indeed shown that cooperative communication would benefit ultimately the robustness of the wireless communication. Probably, one of the major challenge is how to provide cooperative partner instantly to a needy user, where could this be implemented? at the base station or at the base station controller? could the partners for one needy user be many? how could the partner assignment be fair to all and how a mobile user can be convinced to be a partner to other needy user? it should also be noted that the currently conventional basestations need additional capability and the necessary informations to carryout cooperative communication. For instance in the case of detect and forward scheme, the base station should

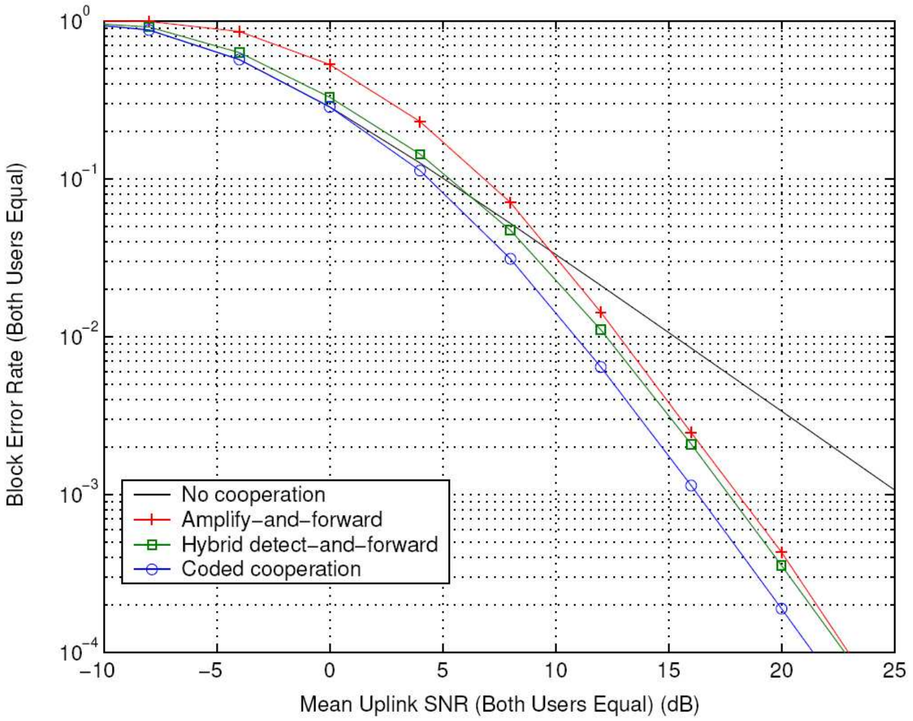

Figure 7: Performance of cooperative signaling methods (-10dB inter-user SNR)

know the error probability of the interuser channel for optimal detection. In the case of coded coooperation the base station needs to know whether users are cooperating or not. On the other hand the transmit and receive requirement needed on the mobiles is not trivial. Here the cooperating mobiles have to detect the uplink signals as well and implementation of the system involves an increased complexity of the receiver. complexity is also increased because, for security purpose, user's data has to be encrypted. For now, these and other unmentioned numerous issues, might halt cooperative communication from being implemented on the current conventional wireless cellular communication. However, the available knowledge should be sufficient to deploy it for wireless sensor networks and ad-hoc networks where there is much flexibility and less scale of deployment to make it financially feasible.

8 Conclusion

In this report recent approaches for cooperative wireless communication is explored. In general, regardless of specific scheme, it was indicated that diversity could be achieved through cooperative communication. This will entail decreased sensitivity to channel variations and improved data rate/throughput. This is a key point (significant enough) for minimum data rate requirement of some real time applications and the resulting lower probability of outage. However for deployment of cooperative communication in the wireless cellular communication there are still numerous challenges to be overcome.

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