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User Cooperation in TDMA Wireless System

Himanshu Katiyar, Babu Sena Paul and R. Bhattacharjee

Communication and Advance DSP Group, Department of Electronics and Communication Engineering, Indian Institute of Technology, Guwahati, India.

Abstract

Reliability of radio link is limited, owing to path loss, shadowing and multi-path fading. This necessitates the use of a certain type of diversity. In recent years, cooperative diversity has gained considerable attention. Here, wireless nodes cooperate in such a way that they share their antennas and other resources, to create a virtual array through distributed transmission and signal processing. This increases coverage and reduces transmitted power, thereby bringing down co-channel interference, which results in increased system capacity. This paper gives an overview of the state of art of various cooperation schemes and issues related to their implementation.

Keywords:
Channel-state estimation, Potential relay, Regenerative and non-regenerative mode, Relay networks, Relay selection, Spatial redundancy.

1. Introduction

Space diversity, which has been widely exploited in wireless communications to combat channel fading, promises higher data rates and larger network coverage [1]. Space diversity is achieved by using multiple antennas at the base station or at the mobile station or at both ends. However, due to the space constraint on certain types of mobile stations, it is difficult to implement multiple antennas maintaining adequate spacing required for diversity system.

A new technique [2], in which multiple spatially separated nodes cooperate to improve the quality of communications between two nodes, is attracting increasing interest. Such systems are able to introduce diversity into the system by using cooperation among nodes, to relay the information to the destination after some delay. In [3], the concept of cooperative diversity was proposed, where one of the nodes behaves as a relay station for other nodes, to boost data rate and decrease sensitivity to channel variations. Such cooperation among nodes may create a virtual antenna array to exploit spatial redundancy, which can significantly increase system capacity. Besides, cooperative diversity has the potential to be successfully used in wireless *ad hoc* networks as well. The wireless *ad hoc* network does not contain a fixed infrastructure and a central control unit such as the base station. The nodes communicate by forming a network based on current channel conditions and node location. This involves node to node communication. In cases where such communication is not reliable, reliability can be improved by making use of relay nodes. Initially, *ad hoc* networks were of interest mostly in military application, but, at present, such networks have widespread commercial application such as in sensor networks, where multiple micro embedded devices are connected to form an autonomous system. The envisioned applications of cooperative sensing emerge as a key technology for tackling the challenges of a practical implementation of cognitive radio [4],[5].

Relay nodes can be broadly categorized as either non-regenerative (analog) or regenerative (digital), depending on their functionality. For the non-regenerative type, a relay simply amplifies and forwards the received signal, while in the latter the relay decodes, encodes, and forwards the received signal. The amplify-and-forward mode of operation puts less processing burden on the relay. Therefore, it is often preferred when complexity and/or latency issues are important. Such relays have been reported to outperform decode-and-forward relays, despite noise propagation, because they do not suffer from error propagation, which limits the performance of decode and forward relaying channels to their weakest link. However, if the channel condition between cooperative radio links is good, regenerative relay does not propagate error in the next stage, because the signal is estimated with very low probability of error and noise free signal is retransmitted. Relay in full duplex mode is difficult in the present state of the art, because of severe attenuation over wireless channel and insufficient electrical isolation between transmitter and receiver circuitry. In Figure 1, S, R and D respectively represent source, relay station and destination. The idea of cooperation among relay was first introduced by van der Meulen [6] and was comprehensively studied in [7]. The capacities of the Gaussian relay channel and certain discrete relay channels were evaluated.

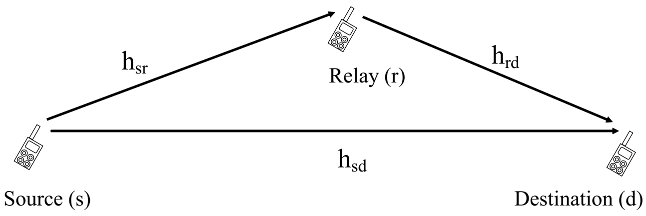

Figure 1: Cooperation between user nodes in TDMA Cellular System.

The capacity of deterministic relay networks with no interference and degraded relay networks was discussed in [8]. General discrete memory-less relay channel was studied in [9]. Schein and Gallager [10] introduced the real, discrete-time Gaussian parallel relay network and present upper and lower bounds of capacity. Recent work on decode-and-forward for multiple relays appeared in [11]. Cooperative diversity schemes, where one user may share another user's resources to improve its transmission rate, have been explored in [12]. Furthermore, these information-theoretic studies of relay networks have motivated practical relaying protocols and code design to achieve user-cooperative diversity and the same has been reported in [13].

Laneman and Wornell [14] developed and analyzed spacetime coded cooperative diversity protocols for combating multipath fading in wireless network. Low complexity cooperative diversity protocols have been studied in [15]. Paper [16] examined the impact of multiple antennas on the performance of the distributed cooperative fixed relays. The capacity regions were investigated for two relay broadcast channels in [17], where relay links were incorporated into two-user broadcast channels, to support user cooperation. In [18], the authors analyzed the distributed selection scheme in cooperative network with multiple transmitting nodes. The impact of interference on cooperative relays in a large wireless system has been studied in [19]. Paper [20] investigated the two schemes, namely cooperative amplify-and-forward with combining solely at the destination and adaptive decode-and-forward with combining at all intermediate nodes. The second scheme has been reported to give better performance in terms of outage probability, at the expanse of additional complexity.

In [21], a cascaded two-hop technique for multi-hop networks employing cooperative relaying has been investigated and the performance of this approach has been evaluated in a generalized rician fading channel. In this context, two new relaying schemes have also been proposed, namely cooperative cascaded 2-hop with resource reuse and cooperative cascaded 2-hop with no resource reuse. The closed form expression for the probability density function of the signal envelope at the output of a selection combiner, having signals from two independent relay channels as inputs, has been reported in [22]. The channel statistics of the individual hops of a relay diversity branch has been assumed to be Nakagami-m distributed. The paper also evaluated the end-to-end density function of a two-hop relay branch. In [23], the authors have presented an expression for the probability density function of the signal envelope at the output of a maximal ratio combiner, having signals from two independent relay channels as inputs.

The end-to-end density function of a two-hop relay branch has also been evaluated. A general analysis of repetition based cooperative relay network, with relays arbitrarily placed between source and destination, has been studied in [24]. Energy issue for such limited energy wireless relays has been considered important. A centralized power allocation technique has been used to optimize the capacity of limited energy wireless relay network. In [25], opportunistic relaying, in which the best relay node is chosen to participate in the transmission, has been studied.

The rest of the paper is arranged as follows: channel modeling and various processing schemes have been discussed in Section II; Section III has dealt with relaying protocols; various cooperation schemes have been discussed in Section IV; some implementation issues of cooperative diversity have been addressed in Section V, with conclusions drawn in Section VI.

2. Channel Modeling and Processing Schemes

2.1 Channel Modeling

A general relay network consists of relay (r), placed between source (s) and destination (d), each node equipped with a single antenna. The relationship between xi input at node i and y_j output at node j can be written as

$$y_i = \sqrt{\rho_{ij}}\, h_{ij} x_i + n_{ij} \tag{1}$$

where i $\in \{s, r_k\}$, j $\in \{r_k, d\}$, parameter $\rho_{i,j}$ represents path gain and shadowing effect of channel between node i and j, $n_{j,j}$ is additive circularly symmetric white Gaussian noise (AWGN), with zero mean and variance $\sigma_{j,j}\,\sigma_{j,j}$(i.e. $E\,(n_{j,j} n^*_{j,j})$) at node j. The node i is assumed to transmit with power P_i (*i.e.* $E\,[x_i x_i^*]$). $h_{ij} = z_{ij} e^{j\theta ij}$ is the complex fading channel coefficient between node i and j. The random variable (RV) Z_{ij} can be modeled as Rayleigh, Rice, Hoyt Nakagami-m etc. The RV Θ_{ij} can be modeled as uniformly distributed in case of Rayleigh; in case of Nakagami-m, it can be modeled as in [[26], eq.(3)].

The Rice distribution is often used to model propagation paths consisting of one strong direct LOS component and many random weaker components. This type of fading is typically observed in the first resolvable line of sight (LOS) paths of micro-cellular urban and suburban land-mobile, pico-cellular indoor and factory environments. It also applies to the dominant LOS path of satellite and ship-to-ship radio links. Hoyt distribution models the scenario of strong ionospheric scintillations, which is typically observed in satellite links. The Nakagami-m fading model provides the flexibility of changing the individual link statistics by changing the parameter *m*. For m = $(1+n^2)^2/1+2n^2$, we get the Rice fading model, taking m = $(1+q^2)^2/2(1+2q^4)$ the channel is made to behave more like a Hoyt channel.

2.2 Processing Schemes

Amplify and Forward (AF): This is an analog scheme, which works in non-regenerative mode. In this scheme, a relay receives the signal, amplifies it and then retransmits it in the next phase. Operation in this mode puts less processing burden on the relay and, hence, is often preferred when complexity and/or latency issues are important.

Decode and Forward (DF): This is a digital scheme, which works in regenerative mode. In this scheme, relay receives the signal, decodes it and, after encoding, retransmits it in the next hop. Noise does not leak in the next stage, but the processing burden on the relay increases.

In lower SNR, its performance degrades because relay cannot decode the massage perfectly; the resulting error will propagate in the next stage.

3. Relaying Protocol

3.1 Cascaded Relaying

In cellular scenario, data-rate suffers if the user is located at the peripheral of the cell or behind the large object (such as hilly territory), due to low signal power. High power transmission is not a feasible solution, due to power constraint of nodes as well as nonlinearities in amplifiers. Besides, co-channel interference increases with increment of transmitted power. Cascaded relaying can be used to increase the coverage area and reduce transmitted power. Thus, co-channel interference will decrease, thereby increasing system capacity. A simple cascaded N_r relay N_r system $\left(i.e.\{r_k\}_{k=1}^{N_r}\right)$ is shown in Figure 2, placed between source (s) and destination (d).

k=1

AF Processing: In amplify–and-forward mode, end-to-end instantaneous SNR received at destination is given by [[27], eq.(8)]

$$y_{sd} = \frac{\prod_{\alpha=1}^{N_r+1} h_{\alpha-1,\alpha} h^*_{\alpha-1,\alpha} G_{\alpha-1} G^*_{\alpha-1}}{\sum_{\alpha=1}^{N_r+1} n_{\alpha,j} \left(\prod_{\beta=\alpha+1}^{N_r+1} G_{\beta-1} G^*_{\beta-1} h_{\beta-1,\beta} h^*_{\beta-1,\beta} \right)} \tag{2}$$

Here, j $\in\{r_k, d\}$ and G_α is complex gain at j. End-to-end instantaneous channel capacity in this mode can be calculated as

$$C_{sd} = \frac{1}{N_r+1} \log\left(1+\gamma_{sd}\right) \tag{3}$$

In the above equation[1], the logarithm is multiplied with $1/(N_r + 1)$ because this system model works in $N_r + 1$ time slots and utilizes only $1/(N_r + 1)$ part of the channel degrees of freedom. Outage probability in this mode is given by

$$P_{out} = P\left[\gamma_{sd} < x\right] \tag{4}$$

Here, χ is the threshold channel SNR.

DF Processing: In decode-and-forward mode, instantaneous SNR between any links is given by

$$\gamma_{ij} = \frac{\rho_{ij} P_i h_{ij} h^*_{ij}}{\sigma_{jj}} \tag{5}$$

End-to-end instantaneous channel capacity in this case is equal to the capacity of its weakest link i.e.

$$C_{sd} = \frac{1}{N_r+1} \min\left(\left\{\gamma_{ij}\right\}\right) \tag{6}$$

Outage probability, in this mode, is given by

$$P_{out} = \prod_{N_r+1} P\left[\gamma_{ij} < x\right] \tag{7}$$

Figure 2: Cascaded relay network, with relay placed between source and destination.

[1]Logarithm is of base 2. This representation is continued in the rest of the paper.

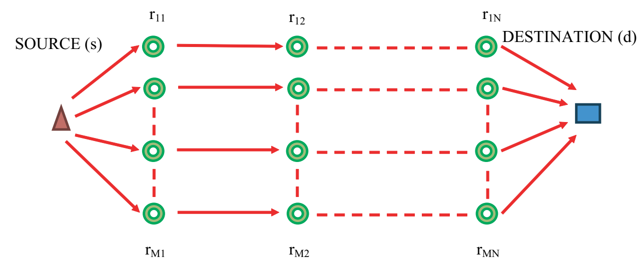

Figure 3: Parallel relay network, with arbiter placed relay structured in matrix of order M ×N between source and destination.

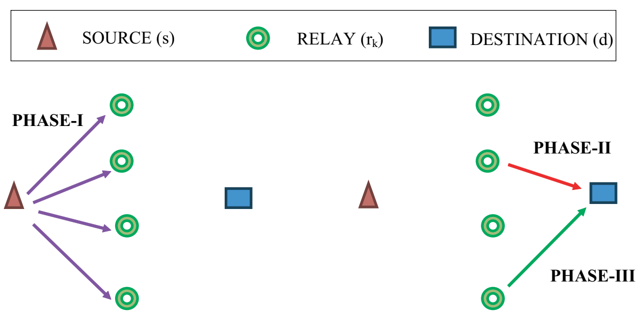

Figure 5: MRC relay network, with arbiter placed relay between source and destination.

Here i $\in\{s, r_k\}$ and j $\in\{r_k, d\}$.

3.2 Parallel Relaying

Parallel relaying provides power gain and diversity gain at the same time. The relay system is structured in the form of a matrix of order $M \times N$, as shown in Figure 3.

AF Processing: In amplify-and-forward mode, instantaneous SNR received at the input of receiver, through k^{th} row of relay matrix, is given by

$$\gamma_{sd}^{kN} = \frac{\prod_{\alpha=1}^{N+1} h_{\alpha-1,\alpha} h_{\alpha-1,\alpha}^{*} G_{\alpha-1} G_{\alpha-1}^{*}}{\sum_{\alpha=1}^{2} n_{\alpha,i} \left(\prod_{\beta=\alpha+1}^{N+1} G_{\beta-1} G_{\beta-1}^{*} h_{\beta-1,\beta} h_{\beta-1,\beta}^{*} \right)} \tag{8}$$

So, the total end–to-end instantaneous SNR received at destination is given by

$$\gamma_{sd} = \sum_{k=1}^{M} \gamma_{sd}^{kN} \tag{9}$$

End-to-end instantaneous channel capacity in this mode can be calculated as

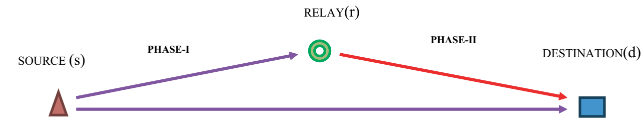

Figure 4: Parallel relay network, with arbiter placed relay between source and destination.

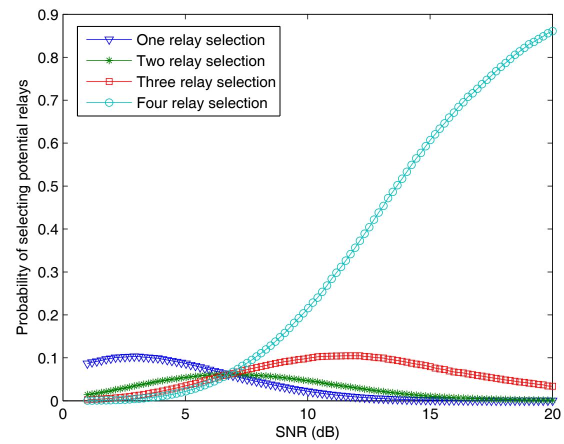

Figure 6: Probability of selecting a number of potential relays from four relay systems in Rayleigh fading channel.

$$C_{sd} = \frac{1}{M+N} \log\left(1+\gamma_{sd}\right) \tag{10}$$

In above equation, the logarithm term is multiplied with $1/(M + N)$ because this system model works in M + N time slots. Here, it is assumed that the special separation between relay matrix in row is sufficiently high; therefore they do not interfere with each other. Outage probability can be calculated from (4).

DF Processing: In decode–and-forward mode, instantaneous SNR between any links is given by (5). To the best of our knowledge, analytical expression for channel capacity for this scenario in decode-and-forward mode is not reported. The channel capacity for a simpler case, as shown in Figure 4, consisting of a single relay between the source and the destination, has been reported in [7]. The end-to-end instantaneous channel capacity is given as [7].

$$C = \frac{1}{2} \min\left\{\log\left(1+\gamma_{sr}\right), \log\left(1+\gamma_{sd}+\gamma_{rd}\right)\right\} \tag{11}$$

Outage probability in case of one relay system is given by

$$P_{out} = P\left[\min\left\{\gamma_{sr}, \gamma_{sd}+\gamma_{rd}\right\} < x\right] \tag{12}$$

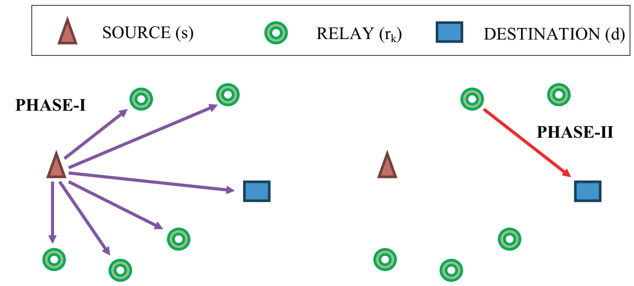

Figure 7: Selection relay network, with arbiter placed relay between source and destination.

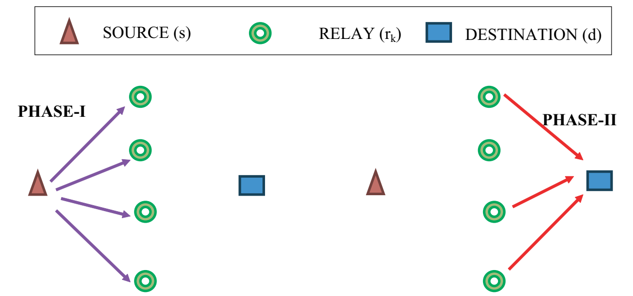

Figure 8: Distributed Space Time Coded network, with arbiter placed relay between source and destination.

4. Cooperation Schemes

4.1 MRC Cooperation

This cooperation scheme (see figure 5) works in the regenerative mode. Firstly, source distributes its message to all relays in first time slot. Those relays, whose SNR from source is good, are able to decode the message successfully. These are called potential relays. The probability of selecting the number of potential relays from four relay systems in the Rayleigh fading channel is shown in Figure 6. These potential relays repeat the message in orthogonal time slots; therefore, this scheme is also known as repetition-based cooperative relaying. Any relay is a member of decoding set D (*s*), if transmit information (I_{rep}) by source is more then the target data rate R (spectral efficiency) [14]:

$$I_{rep} = \frac{1}{|D(s)|+1}\log\left(1+\gamma_{s,r_k}\right) \ge R \tag{13}$$

In (18), the logarithm is multiplied with 1/(D (*s*)+1) because only that fraction of the channel is utilized. Here D (*s*) is the cardinality of set D (*s*). The probability of any relay becoming a part of the decoding set is given by

$$P\left[r_k \in D(s)\right] = P\left[\gamma_{sr_k} \ge x\right] \tag{14}$$

Here $\chi = 2^{(|D(s)|+1)R} - 1$ is the threshold channel power. Moreover, since each potential relay makes its decision independently and the fading coefficients are independent, the probability of choosing any decoding set is

$$P\left[D(s)\right] = \prod_{r_k \in D(s)} P\left[r_k \in D(s)\right] \times \prod_{r_k \notin D(s)} \left(1 - P\left[r_k \in D(s)\right]\right) \tag{15}$$

Using the probability law, outage probability can be written as

$$P\left[I_{rep} < R\right] = \sum_{D(s)} P\left[D(s)\right] P\left(I_{rep} < R / D(s)\right) \tag{16}$$

Here, P [I_{rep} <*R*/D (*s*)] is conditional outage probability. In (16), the summation is over all the possible decoding set D (*s*). In this algorithm, bandwidth efficiency decreases as the number of decoding relays increases. Instantaneous capacity of opportunistic relay network is given by [14]

$$C^{rep} = \frac{1}{|D(s)|+1}\log\left(1 + \sum_{r_k \in D(s)} \gamma_{r_k,d}\right) \tag{17}$$

4.2 Selection Cooperation

In the regenerative mode, the source transmits message along with training sequence, which is received by all the relay nodes (r_k) and destination (d) (see figure 7). From these training sequences, relay estimates channel quality and becomes potential relay, if the channel quality is good. All potential relays transmit training sequence to destination; therefore, the information of channel quality from relay is available to the destination. The destination node compares all channel SNR and allows the best relay to forward message in next hop. Message transmitted by the source in the first hop and the forwarded message in the second hop by best potential relay are coherently combined by the destination node. Any relay becomes the potential relay of decoding set D (*s*), if the transmitted information (I_{oper}) by source is more than the target data rate R (spectral efficiency) [14]:

$$I_{oper} = \frac{1}{2}\log\left(1+\gamma_{s,r_k} \ge R\right) \tag{18}$$

The logarithm term is multiplied with 1/2 because this system model works in two time slots and utilizes only half the channel degree of freedom. The probability of any relay is in the set of decoding set and the probability of choosing any decoding set can be calculated from (14) and (15) respectively. Using the total probability law, the outage probability can be written as

$$P\left[I_{oper} < R\right] = \sum_{D(s)} P\left[D(s)\right] P\left[I_{oper} < R / D(s)\right] \quad (19)$$

Instantaneous capacity of opportunistic relay network is given by [14]

$$C^{oper} = \frac{1}{2}\log\left(1 + \gamma_{s.d} + \max_{r_k \in D(s)}\left(\gamma_{r_k,d}\right)\right) \quad (20)$$

4.3 Cooperation Through Distributed Space Time Coding

Such protocols operate in a fashion similar to the repetition-based cooperative diversity algorithm, except that all the relays transmit simultaneously on the same subchannel, using a suitable space-time code (see figure 8). The protocols of this form offer full spatial diversity in the number of cooperating terminals, not just the number of decoding relays participating in the second phase. In addition, these algorithms have bandwidth efficiency superior to repetition-based algorithms. In practice, such code design is quite difficult, due to the distributed and *ad hoc* nature of the cooperative links, as opposed to colocated multiple-input multiple-output (MIMO) systems. For example, it is impractical for each relay to acquire channel state information (CSI) about other relays or for the destination to acquire CSI between the source and all relays. Hence, the states of those channel need to be communicated to each relay or destination. Moreover, the number of useful antennas (distributed relays) for cooperation is generally unknown and varying. Therefore, coordination among the cooperating nodes is needed prior to a specific spacetime coding scheme, designed for a fixed number of transmit antennas. Furthermore, it is often assumed in literature that the superposition of signals transmitted by several relays is always constructive. Such assumption requires distributed phased-array techniques and unconventional radios with increased complexity and cost of each transmitter. Finally, coherent reception of multiple relay transmissions requires tracking of carrier phase differences among several transmit-receive pairs, which increases the cost of the receiver.

5. Implementation Issues

Multi-path fading is the main hurdle for high data rate communication in wireless environment. Diversity in time, frequency or space can nullify the effect of fading. Diversity in time and frequency is difficult to implement in band limited system, because of limited resources. Exploitation of spatial diversity is one of the possible solutions for band limited system. Diversity gain can be achieved through MIMO system, but it is difficult to implement multiple antennas in hand-held wireless terminals.

Cooperative diversity has a lot of potential and it is gaining considerable attention in recent years. It is too nascent to be implemented in real scenario, due to some interesting challenges such as: who will cooperate with whom, under what conditions will they cooperate, at which point on the achievable rate region will they operate and why, and who decides which users partner - the users themselves or the base station (BS). For example, when two users face statistically similar channels toward the destination node, the issue is easy: both users benefit, and, therefore, both would like to cooperate. However, when the two users face statistically dissimilar channels toward the destination node, as would occur if user one was near the outskirts of the cell and the user two was near the center of the cell, the situation becomes complicated. The question arises why one user would be willing to give up some of its data rate and precious battery power to other user, when doing so is not beneficial to it.

In the coming years, cooperative relaying will have applications in the fields of advanced cellular networks, wireless sensor network, *ad hoc* networks etc., once the above issues are addressed by standardization bodies and groups.

6. Conclusions

Cooperative diversity is a way to form virtual antenna arrays that decrease the sensitivity to channel variations and increase the data rate. For better quality of service, minimum data-rate is essential for some real-time applications such as voice or video, which can be achieved through cooperation in fading environment. Increased data rate, with this technique, can also be translated into reduced power for the users. Users need to use lesser amount of total power to achieve a certain rate, than with no cooperation, and this extends the battery life of the mobile nodes. Alternatively, cooperation gains may be used to increase cell coverage in a cellular system. Apart from this, cooperative diversity has a wide application in *ad hoc* networks and wireless sensor networks. In the absence of any central unit, the functionality of such networks will not be effected if any node becomes out of order.

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AUTHORS

Himanshu Katiyar received his B.Tech degree in Electronics and Communication from M.J.P. Rohilkhand University, Bareilly, Uttar Pradesh, India in 2001 and M.Tech from Madan Mohan Malviya Engineering College, Gorakhpur, Uttar Pradesh, India in 2004. From 2004-2005 he was lecturer of Electronics and Communication Engineering Dept. at SRMSCET, Bareilly, Uttar Pradesh, India and from 2005-2006 he was lecturer of Electronics and Communication Engineering Dept. at NIEC, Lucknow, Uttar Pradesh, India. He is currently pursuing his Ph.D. in area of wireless communication at Indian Institute of Technology (IIT), Guwahati, Assam India. His research interests include almost all aspects of wireless communications with a special emphasis on MIMO systems, channel modeling, infrastructure-based multihop and relay networks, cooperative diversity schemes.

E-mail: h.katiyar@iitg.ernet.in

Babu Sena Paul received his B.Tech and M.Tech degree in Radio physics and Electronics from the University of Calcutta, West Bengal, India, in 1999 and 2003 respectively. He was with Philips India Ltd from 1999-2000. From 2000-2002 he was lecturer of Electronics and Communication Engineering Dept. at SMIT, Sikkim, India. He is currently pursuing his Ph.D. in the area of wireless communication at IIT Guwahati, Assam, India. He has attended and published several papers in international and national conferences and symposiums. He was awarded the IETE Research Fellowship. He is a life member of IETE.

E-mail: babusena@iitg.ernet.in

Ratnajit Bhattacharjee received his B. E. in Electronics and Telecommunication Engineering (First Class Honors) from Gauhati University (REC (at present NIT) Silchar), M. Tech. (E and ECE Department, Microwave Engineering specialization) from IIT Kharagpur and Ph. D. (Engineering) from Jadavpur University Kolkata. Presently he is an Associate Professor in the Department of Electronics and Communication Engineering, IIT Guwahati. Prior to joining IIT Guwahati, he was a faculty member in REC (NIT) Silchar. His research interest includes Wireless communication, Wireless networks, Microstrip antennas, Microwave Engineering and Electromagnetics. He has published over sixty research papers in journals, international and national conferences. He has developed the web course on Electromagnetic Theory under the NPTEL project of MHRD. He has also been involved in several research projects. He has been a Co-investigator for the contracted research from NICT Japan in the area of Next Generation Wireless Networks and currently a member of the research team of the Tiny6 STIC project (funded by French ministry of Foreign Affairs), which deals with IPv6 and Sensor Networks. In NIT Silchar, he was a coordinator for the setting up of Campus Wide Optical Fiber based network under the Centre for Excellence scheme. He was also associated in a number of sponsored projects in the field of development of antenna system. He is a member of IEEE and life member of Indian Society of Technical Education.

E-mail: ratnajit@iitg.ernet.in