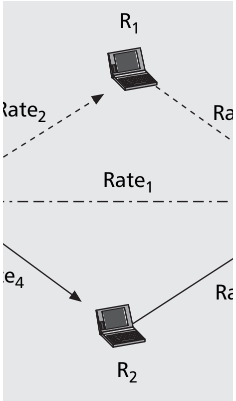
ADVANCES IN SMART ANTENNAS

COOPERATIVE WIRELESS COMMUNICATIONS: A CROSS-LAYER APPROACH

PEI LIU, ZHIFENG TAO, ZINAN LIN, ELZA ERKIP, AND SHIVENDRA PANWAR,
POLYTECHNIC UNIVERSITY



In cooperative communications, multiple nodes in a wireless network work together to form a virtual antenna array. Using cooperation, it is possible to exploit the spatial diversity of the traditional MIMO techniques without each node having multiple antennas.

ABSTRACT

"Denise and her husband Mitch are at opposite ends of a living room at a crowded party. Denise tries to attract Mitch's attention and shouts something at him. All Mitch can hear is the word 'Let's.' Celine, in the middle of the room, who overhears Denise and notices their predicament, repeats to Mitch the part she hears: 'Go home.' This time, all Mitch hears is the word 'home.' Mitch finally figures out that his wife wants to go home." This analogy from everyday life vividly portrays the essential element of cooperative wireless communications, namely, utilizing information overheard by neighboring nodes to provide robust communication between a source and its destination. Cooperative communication exhibits various forms at different protocol layers and introduces many opportunities for cross-layer design and optimization, some of which will be explored in detail in this article.

INTRODUCTION

The burgeoning demand for mobile data networks has highlighted some constraints on its future growth. Wireless links have always had orders of magnitude less bandwidth than their wireline counterparts. Mobile users have always chafed at this limitation, which essentially forces them to use applications in a manner reminiscent of wireline networks of decades past, albeit freeing them from a desktop. Newer technologies such as multiple-input multiple-output (MIMO) systems are starting to increase the number of bits per second per hertz of bandwidth through spatial multiplexing, and to improve the robustness/range of the wireless link for a given data rate through space-time coding and beamforming. However, all these improvements come at the cost of multiple RF front ends at both the transmitter and the receiver. Furthermore, the size of the mobile devices may limit the number of antennas that can be deployed. Even when MIMO technology is feasible, wireless engineers are running into another roadblock: the inefficient way the electromagnetic spectrum has been allocated to different classes of users, mainly for historical or regulatory reasons. Thus, while large portions of the spectrum are grossly underused, the popular unlicensed bands are very crowded. Given this limitation, for unlicensed bands, the issue of interference from having too many users has become as important as how much bandwidth can be squeezed from it.

This article outlines one way to address these problems by using the notion of cooperation between wireless nodes. In cooperative communications, multiple nodes in a wireless network work together to form a *virtual antenna array*. Using cooperation, it is possible to exploit the spatial diversity of the traditional MIMO techniques *without* each node necessarily having multiple antennas. Multihop networks use some form of cooperation by enabling intermediate nodes to forward the message from source to destination. However, cooperative communication techniques described in this article are fundamentally different in that the relaying nodes can forward the information fully or in part. Also the destination receives multiple versions of the message from the source, and one or more relays and combines these to obtain a more reliable estimate of the transmitted signal as well as higher data rates. The main advantages of cooperative communications are:

- Higher spatial diversity: resistance to both small scale and shadow fading
- Higher throughput/lower delay: higher achievable data rates, fewer retransmissions, and lower transmission delay
- Reduced interference/lower transmitted power: better frequency reuse in a cellular/WLAN deployment
- Adaptability to network conditions: opportunistic use and redistribution of network energy and bandwidth

The past few years have seen tremendous interest in cooperative communications, mostly at the physical layer. However, significant research challenges still exist, some of which we outline in this article.

The goal of this article is to provide new

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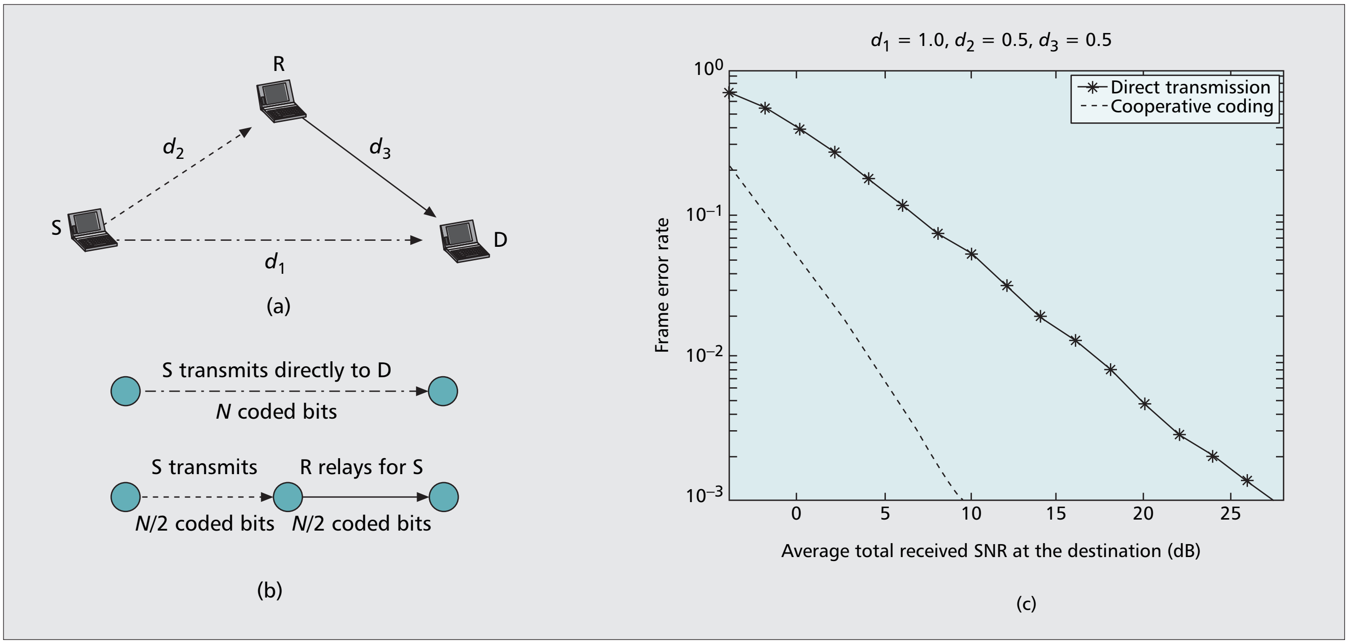


Figure 1. *a) Cooperative system for an isolated link; b) time division in cooperative coding; c) two user cooperative coding performance for* $d_1 = 1$, $d_2 = 0.5$ *and* $d_3 = 0.5$, *(13, 15, 15, 17) convolutional code, 100-byte frame size.*

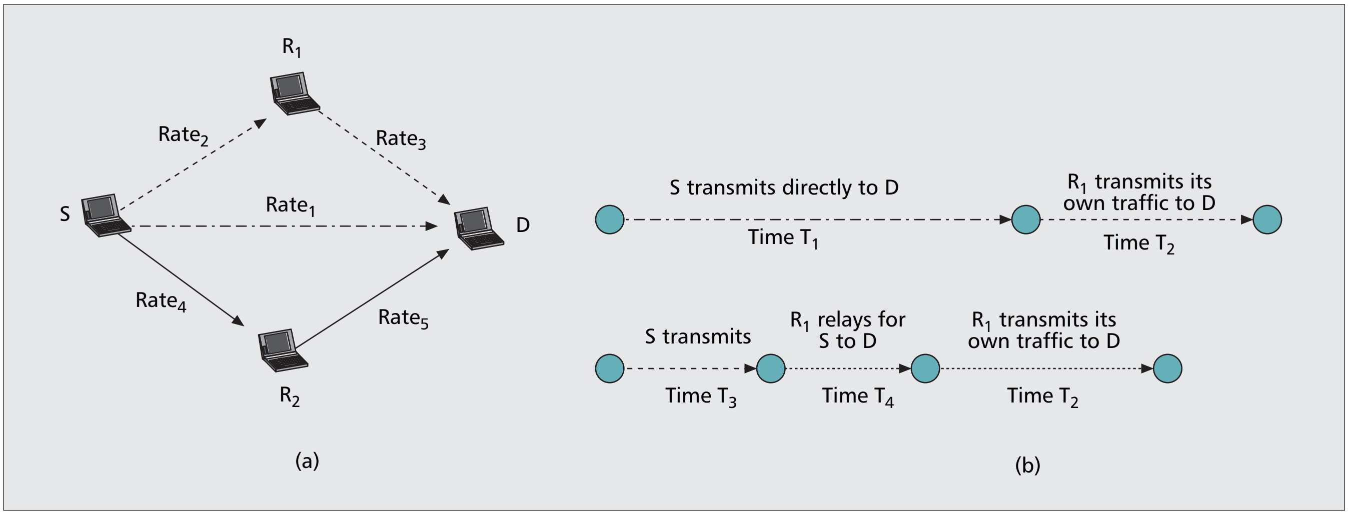
cross-layer research directions in order to illustrate the feasibility and performance of cooperative wireless networking. We first describe the notion of physical-layer cooperation and cooperative diversity. However, in order to realize a fully cooperative network, research at the physical layer should be coupled with higher layers of the protocol stack, in particular, the MAC sublayer and the network layer. We describe how physical-layer cooperation can be integrated with the MAC sublayer for dramatic improvements in throughput and interference. We also outline some of the challenges in extending the notion of cooperative diversity to the network layer.

MOTIVATION FOR COOPERATIVE COMMUNICATION

In this section we introduce the basic concepts underlying cooperative communications. Cooperative techniques utilize the broadcast nature of wireless signals by observing that a source signal intended for a particular destination can be "overheard" at neighboring nodes. These nodes, called *relays*, *partners*, or *helpers*, process the signals they overhear and transmit towards the destination. The relay operations can consist of repetition of the overheard signal (obtained, for example, by decoding and then re-encoding the information or by simply amplifying the received signal and then forwarding), or can involve more sophisticated strategies such as forwarding only part of the information, compressing the overheard signal, and then forwarding. We refer the reader to [1] for a detailed overview of relaying methods. The destination combines the signals coming from the source and the relays, enabling higher transmission rates and robustness against channel variations due to fading. We note that the spatial diversity arising from cooperation is not exploited in current cellular, wireless LAN, or ad hoc systems; only one copy of the signal, whether it comes from the mobile directly or from a relay, is processed at the destination. Hence, cooperative relaying is substantially different than traditional multihop or infrastructure based methods.

This notion of cooperation dates back to the relay channel model in information theory extensively studied in the 1970s by Cover and El Gamal [2], but we owe the recent popularity to [3–5], which showed the benefits of cooperative relaying in a wireless environment. In order to illustrate the idea of cooperation and cooperative diversity at the physical layer, we consider the cooperative coding scheme used in [6, 7]. Let us consider an isolated source S who wants to communicate with a destination D with the help of a cooperative relay R, as illustrated in Fig. 1a. Here, d_i denotes the distances between the nodes.

For direct transmission (i.e., if the relay R is not utilized), each channel block, or packet, contains B data bits and r parity bits for forward error correction (FEC), leading to a total of $N = B + r$ *coded bits*, as shown at the top of Fig. 1b. For ease of exposition, we have $r \geq B$. We assume that cyclic redundancy check (CRC) is employed for error detection. In order to cooperate, S divides its channel block into two and only transmits in the first half, as shown at the bottom of Fig. 1b. Hence, in the cooperative mode S ends up sending only half of its coded bits. These bits are received both by the destination and by the relay R. The relay observes a higher coding rate and thus a weaker FEC. Nevertheless, it attempts to decode the underlying B data bits. If R has the correct information (which can be checked using the CRC), it re-encodes and sends the remaining $N/2$ parity bits in the second half of S's time slot. Otherwise, R informs S that there was a failure in decoding, and S continues transmission. Therefore, when R decodes correctly,



■ **Figure 2.** *a) Cooperation in a network; b) illustration of the delay and throughput improvement achieved by cooperation in the time domain.*

the destination will receive half the coded bits from *S* and the remaining ones from *R*, thus creating spatial diversity. The question is how often this happens and how it affects the overall error performance.

Figure 1c illustrates simulation results for frame error rate (FER) versus the total transmit signal-to-noise ratio (SNR) for the scenario where the relay is located halfway between the source and destination (i.e., $d_1 = 1.0$, $d_2 = 0.5$, and $d_3 = 0.5$). Note that direct transmission and cooperative coding use the same total power and bandwidth (we consider a low-mobility environment). Hence, along with path loss, we assume all links experience independent slow Rayleigh fading that stays constant for the duration of each packet. The nodes use convolutional coding and each node has the same average power constraint. We observe from the figure that for an error rate of 10^{-3} we obtain about 18 dB improvement in SNR with cooperation. Also, the FER for cooperative coding decreases at a much faster rate than direct transmission; in fact, cooperation is able to achieve two full levels of diversity similar to a MIMO system with two transmit antennas and one receive antenna.

The above example considers one particular cooperative scheme to obtain diversity, yet it shows the potential of cooperation at the physical layer. Indeed, there is a rich literature on physical-layer cooperation that investigates many aspects, such as cooperative protocols for two or more users, performance bounds for cooperative systems, resource allocation for cooperation, and partner-choice strategies. Using a cross-layer approach between physical and MAC layers, this article investigates how these gains can be attained in a wireless network.

BENEFITS OF COOPERATIVE NETWORKING

From the perspective of the network, cooperation can benefit not only the nodes involved, but the whole network in many different aspects. For illustration purposes, we choose to explain only a few potential benefits below.

HIGHER SPATIAL DIVERSITY

As a simple example, Fig. 2a shows a small network of four mobile nodes. If the channel quality between mobile nodes *S* and *D* degrades severely (e.g., due to shadow or small-scale fading), a direct transmission between these two nodes may experience an intolerable error rate, which in turn leads to retransmissions. Alternatively, *S* can exploit *spatial diversity* by having a relay R_1 overhear the transmissions and then forward the packet to *D* as discussed above. The source *S* may resort to yet another terminal R_2 for help in forwarding the information, or use R_1 and R_2 simultaneously [8]. Similar ideas apply to larger networks as well. Therefore, compared with direct transmission, the cooperative approach enjoys a higher successful transmission probability. We note here that cooperative communications has the ability to adapt and to mitigate the effects of shadow fading better than MIMO since, unlike MIMO, antenna elements of a cooperative virtual antenna array are separated in space and experience different shadow fading.

HIGHER THROUGHPUT-LOWER DELAY

At the physical layer, rate adaptation is achieved through adaptive modulation and adaptive channel coding. Many MAC protocols have introduced rate adaptation to combat adverse channel conditions. For instance, when a high channel-error rate is encountered due to a low average SNR, the wireless LAN standard IEEE 802.11 switches to a lower transmission rate so as to guarantee a certain error rate. The power of cooperation is evident when it is applied in conjunction with any rate adaptation algorithm. In Fig. 2a, specifically, if $Rate_2$ and $Rate_3$ are higher than $Rate_1$ such that the total transmission time for the two-hop case through R_2 is smaller than that of the direct transmission, cooperation readily outperforms the legacy direct transmission, in terms of both throughput and delay perceived by the source *S*. Furthermore, for relays such as R_1 and R_2, it turns out that their own individual self-interest can be best served by helping others.

As further illustrated in Fig. 2b, the intermediate node R_1 that cooperates enjoys the benefit of lower channel-access delay, which in turn can be translated into higher throughput. It is worthwhile to note that Fig. 2b also draws a rough analogy with the cooperative scheme discussed above (Fig. 1b) and illustrates that rate adaptation can further improve the benefits of cooperation in a network setting.

LOWER POWER CONSUMPTION AND LOWER INTERFERENCE/EXTENDED COVERAGE

The diversity, error rate, and throughput gains obtained through cooperation can be traded in for power savings at the terminals. Alternatively, cooperation leads to an extended coverage area when the performance metric (error rate, throughput, etc.) is fixed.

The advantage of cooperation also leads to reduced interference when the network is deployed in a cellular fashion to reuse a limited bandwidth. With the improvement of throughput, we can reduce the average channel time used by each station to transfer a certain amount of traffic over the network. Therefore, the signal-to-interference ratio (SIR) between proximal cells using the same channel can be reduced, and a more uniform coverage can be achieved. As wireless network deployments become ever more dense, a reduction of SIR will directly lead to a boost in network capacity. Indeed, the problem of dense deployment has already been reported for IEEE 802.11 b/g networks, which have only three nonoverlapping channels.

ADAPTABILITY TO NETWORK CONDITIONS

The cooperative communication paradigm allows wireless terminals to seamlessly adapt to changing channel and interference conditions. The choice of relays, cooperation strategy, and the amount of resources available for cooperation can be opportunistically decided. For example, in Fig. 2a, if the source S has some information about the current channel gains, packet-loss rates, traffic conditions, interference, or remaining battery energy of nodes in the network, it may choose to transmit its information directly to its destination D, using R_1 or R_2 or both in a cooperative fashion, depending on which transmission mode results in better performance (in terms of error rates, throughput, or power). This way, a surplus of resources such as battery energy or bandwidth at a particular node can be utilized by other nodes in the network in a manner that will benefit everyone, including the relay node itself.

Although originating from physical-layer cooperation, all the aforementioned benefits cannot be fully realized until proper mechanisms have been incorporated at higher protocol layers (e.g., MAC, network) and the necessary information is made available from the lower layer (e.g., PHY). Indeed, a cross-layer approach has to be followed to reap all the benefits of cooperation. As we illustrate via the cooperative MAC protocol described in the following section, an additional three-way handshake procedure and a new signaling message have to be introduced to the MAC layer, and information on channel conditions for related wireless links should be made available to the upper layers so that the cooperation can be fully enabled. Another example of a cross-layer approach to cooperation, which involves interaction between the application layer and the physical layer, is provided in [9] for transmission of video signals over wireless links.

COOPMAC: A COOPERATIVE MEDIUM ACCESS CONTROL

As described above, cooperation at the physical layer uses the broadcast nature of the wireless medium and overheard information to improve the performance. Unfortunately, conventional wireless medium access control (MAC) protocols have long treated this feature as a problem, rather than something that can be exploited. The methodology of cooperation, however, embraces this concept, and thus creates a new paradigm for MAC protocol design in wireless network.

We present a new MAC protocol called CoopMAC[1] for IEEE 802.11 wireless LANs, which exploits both the broadcast nature of the wireless channel and cooperative diversity. As we demonstrate, the CoopMAC protocol fully capitalizes on the notion of cooperation, and realizes some of the key benefits previously highlighted, such as higher throughput, lower delay, better coverage, and reduced interference. In the end, we briefly discuss a preliminary CoopMAC implementation.

Zhao and Valenti also consider a MAC protocol [11] for exploiting cooperative diversity, but it is based upon a conceptual generalization of the hybrid automatic repeat request scheme (hybrid-ARQ), instead of the widely deployed 802.11 protocol. Recently, there have been attempts to explore the benefits of virtual MIMO at the network level, by pursuing a cross-layer approach spanning the physical, MAC, and networking (e.g., routing) layers [12]. However, the proposed scheme is based on the assumption that multiple nodes can be perfectly synchronized. Although the protocol mechanism proposed herein bears some resemblance to that described in [13], the two protocols address fundamentally different issues in two distinct problem spaces. More specifically, rate adaptation is the main focus of [13], while cooperative diversity is incorporated in the protocol introduced here.

COOPMAC PROTOCOL DESCRIPTION

- When a source node has a new MAC protocol data unit (MPDU) to send, it can either transmit directly to the destination, or use an intermediate helper for relaying, whichever consumes less total air time. The air time is compared using cached information on the feasible data rates between the three nodes. The feasible data rate is the largest data rate that guarantees a predetermined average error rate threshold for an average channel SNR.
- Beyond its normal function, a request to send (RTS) message is also used by CoopMAC to notify the node that has been selected for

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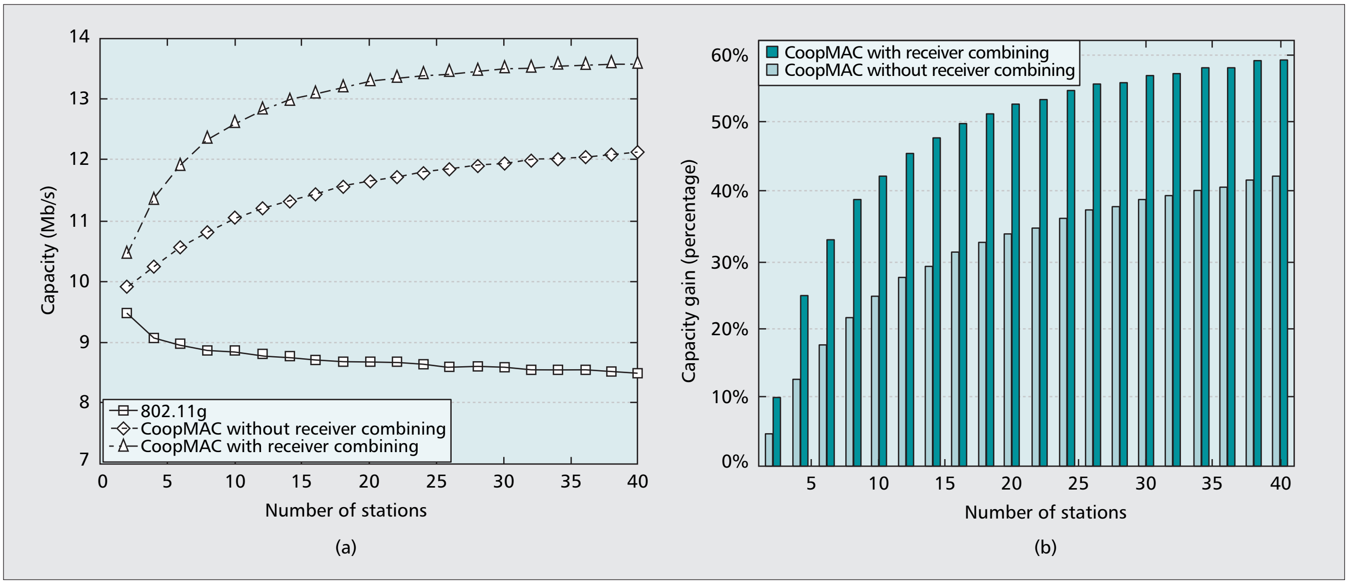
[1] *A preliminary version of the CoopMAC protocol was described in [10].*



(a)

(b)

Figure 3. *Network capacity comparison: a) saturation capacity; b) network capacity gain with respect to 802.11g.*

cooperation. Moreover, CoopMAC introduces a new message called helper-ready to send (HTS), which is used by the helper to indicate its availability after it receives the RTS message from the source. If the destination hears the HTS message, it issues a clear to send (CTS) message to reserve channel time for a two-hop transmission. Otherwise, it still sends out the CTS, but only reserves channel time for a direct transmission.

- If both HTS and CTS are received at the source, the data packet should be transmitted to the relay first, and then forwarded to the destination by the relay. If the source does not receive an HTS, it should then initiate a direct transmission to the destination.
- A normal ACK is used to acknowledge a correct reception, regardless of whether the packet is forwarded by the relay, or is directly transmitted from the source. If necessary, retransmission is attempted, again in a cooperative fashion.

It is crucial that each node obtains and constantly updates its information about the availability of potential relays. The CoopMAC protocol deals with this issue mainly through maintaining a table called the *CoopTable* in its management plane. Each entry in the CoopTable corresponds to a potential relay, and contains such information as the *ID* (e.g., 48-bit MAC address) of the potential relay, the latest time at which a packet from that potential relay is overheard by the source, and the data rate used for direct transmission between the potential relay and destination, and between the current node and the potential relay. A set of protocols have been defined in CoopMAC to properly establish, manage, and update the table in a timely manner.

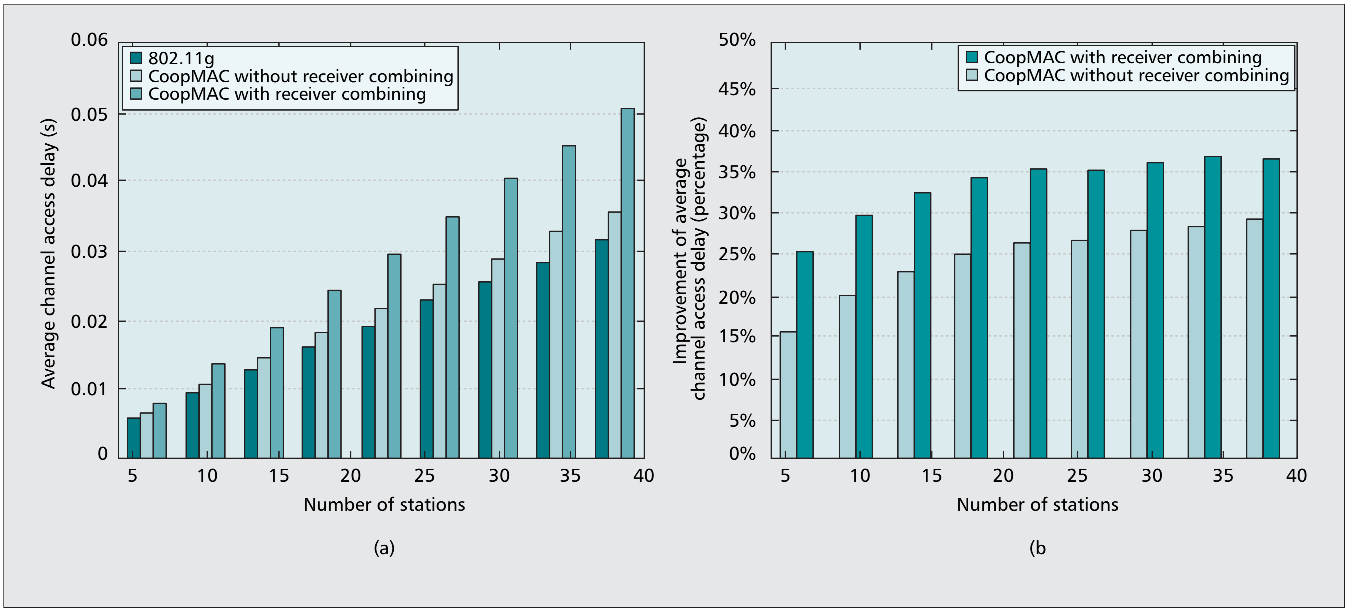
Due to the broadcast nature of the channel, the destination will receive the signals transmitted by both the source and the relay. If the destination is capable of combining these two copies to decode the original information, then cooperative diversity can be fully leveraged. Receiver combining, not supported by any existing wireless hardware, can be implemented in the next-generation wireless baseband chip. Given the constraint of using existing hardware, we have developed a backward compatible mode of CoopMAC, which does not perform receiver combining and therefore only requires a driver or firmware upgrade.

Without diversity combining: If no combining capability is supported at the destination, the packet should be transmitted on both the first and second hop at the highest physical layer rate that the respective link can sustain.

With diversity combining: When receiver combining is enabled, the relay now can forward packets at a rate equal to or greater than the one that it adopts in CoopMAC where combining is not possible. More specifically, the transmission rate between the source and relay is chosen so as to guarantee a desired error probability at the relay. Although the destination cannot fully decode the packet after the first-hop transmission, this received signal will be stored. If the relay can successfully receive the packet, it then forwards the packet to the destination. The transmission rate on the second hop is the highest one that meets a predetermined average error rate at the destination, once the destination combines the source and relay signals.

The diversity combining capability allows CoopMAC to leverage both the spatial diversity and the coding gain, thereby resulting in even better performance than the protocol without receiver combining. Using the coded cooperation framework described above, the helper provides different coded bits than the source, leading to a better error performance than repetition coding.

It is worthwhile to note that although the protocol architecture and signaling mechanism defined above are applicable both with and without diversity combining at the receiver, the relay-selection scheme may not yield an optimal choice for CoopMAC with receiver combining any longer, because it does not take the possible



■ **Figure 4.** *Channel access delay comparison: a) mean channel access delay; b) improvement of mean channel access delay with respect to 802.11g.*

rate increase on the second hop into consideration. In addition, the relay has to be aware of the average link quality (e.g., average SNR) between the source and destination so that it can properly select a higher transmission rate on the second hop. The information can be easily conveyed to the relay by sandwiching a “shim” *link quality* field between the legacy MAC header and the MAC payload in the data packets that the source transmits.

Although CoopMAC bears some superficial resemblance to conventional ad hoc routing protocols, they are in essence completely different. First and foremost, forwarding in CoopMAC is an essential means to accomplish the goal of leveraging cooperative diversity. Secondly, all the associated operations occur in the MAC layer, which enjoys a shorter response time and more convenient access to the physical layer information, as compared to the traditional network layer routing. In addition, no channel contention is needed when the relay forwards the packets to the destination, thereby leading to a shorter delay for the relay and a more efficient channel utilization as well. Last but not the least, no routing protocol that we are aware of has adopted the receiver-combining technique to tap into the potential of cooperative diversity.

THROUGHPUT, DELAY, AND ENERGY EFFICIENCY OF COOPMAC

To evaluate the performance of CoopMAC, we have developed an event-driven custom simulator using the programming language C to faithfully model all the critical MAC and physical layer features of IEEE 802.11 and CoopMAC. The parameters in the performance evaluation assume the default values specified for an IEEE 802.11g network operating in a typical office environment with low user mobility.

Figures 3–5 depict the simulation results for a saturated network with a payload size of 1500 bytes. The MSDU size of 1500 bytes has been chosen in the simulation because the data packets usually assume such a length in wireless LANs, as widely reported in recent traffic pattern research [14]. *Saturation* here refers to a MAC-level condition, where each station always has packets to transmit at any time instant. Note, however, that the MAC-level saturation does not necessarily imply that the physical wireless channel is always occupied, as all the stations have to perform backoff according to the random-access MAC protocol.

As demonstrated in Fig. 3, both flavors of CoopMAC can achieve a much higher network capacity than the legacy IEEE 802.11g. Between the two versions of CoopMAC, the one with receiver-combining capability can deliver more throughput, as was anticipated above.

Another highly desirable feature of CoopMAC that Figs. 3a and 3b reveal is that both the network capacity and the capacity gain for CoopMAC with respect to 802.11g *increase* as the number of nodes in the network grows. This improvement primarily stems from the increasing availability of relays as the network becomes more populated.

For a wide variety of network sizes, Fig. 4 portrays the simulation results for the average channel access delay, which essentially is the duration from the time a packet becomes the head-of-line (HOL) packet until the time the packet is successfully transmitted. The corresponding delay improvement over 802.11g is shown in Fig. 4b. It is evident that data packets in CoopMAC experience significantly less delay than in legacy IEEE 802.11g.

It is also worthwhile to note that the same trend in throughput and delay improvement can be observed for networks operating in a medium-to-low-traffic regime. In addition, even more improvement can be achieved when a larger frame size is used. Due to space limitations, we will not present additional results in this article

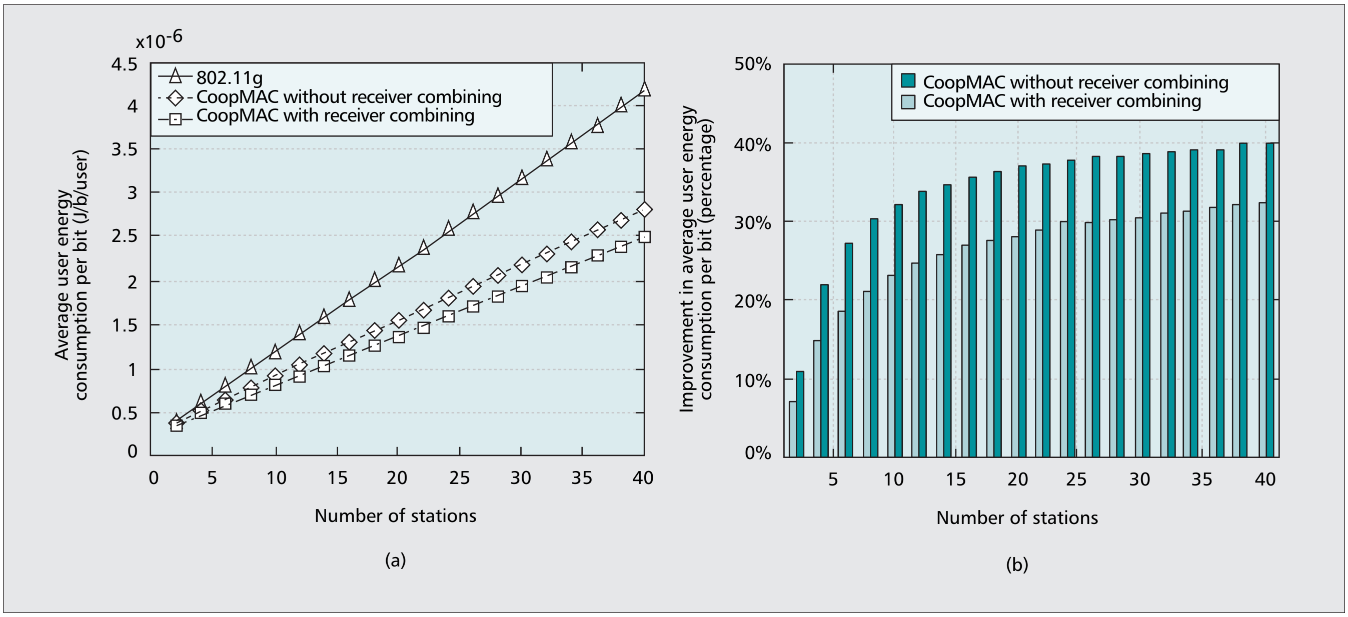


Figure 5. *Energy efficiency comparison: a) average energy consumption per bit per user; b) average user energy efficiency gain with respect to 802.11g.*

for the nonsaturation condition or for larger frame sizes.

In addition to conventional measures like throughput and delay, we have also evaluated the energy efficiency of CoopMAC, since power conservation is always a key concern for wireless networks. Figure 5a depicts the energy consumption per user in terms of total amount of energy needed to successfully deliver a bit for each user (i.e., joules/bit/user), which includes the energy consumed in transmission, reception and channel sensing. Figure 5b shows the percentage improvement with respect to 802.11g. We observe that as the number of nodes increases, the improvement in per user energy efficiency achieved by CoopMAC also grows. This is primarily due to the fact that although CoopMAC requires nodes to receive and retransmit traffic for each other, it also enables them to spend less time listening to the medium. Ultimately, this saving outweighs the new energy expense, and leads to an increase in energy efficiency. We refer the readers to [15] for details of the energy-consumption model.

INTERFERENCE REDUCTION IN A DENSE NETWORK

The deployment of wireless networks has grown increasingly dense, leading to concerns that deployments may become interference-limited. For instance, there are 11 channels defined in the 2.4 GHz spectrum for operation of IEEE 802.11 WLANs in the United States. However, in order to avoid interference between adjacent cells, only three mutually nonoverlapping channels can be used at the same time.

In the following discussion, we focus only on co-channel interference for a cellular deployment of IEEE 802.11 with a *reuse* factor of three. Note that while a node is transmitting packets in a particular cell, there will be six proximal cells in which parallel transmissions generate co-channel interference. Our simulation calculates the signal-to-interference-plus-noise ratio (SINR) for each point in a cell by randomly choosing the locations of six interfering nodes in the six proximal cells and assuming path loss as well as Rayleigh fading. The maximum feasible data rate is estimated based on the SINR and the error rate threshold requirement.

Figure 6 compares the interference for 802.1 ig MAC and CoopMAC in a multicell environment with a frequency reuse factor of three. All three systems are under the same traffic load in all cells. From these figures, another advantage of cooperation becomes apparent. CoopMAC without receiver combining decreases the average interference by 21.5 percent, while receiver combining enables another 12.5 percent reduction. Since both versions of CoopMAC are more efficient in terms of throughput, the transmission time for the same amount of traffic using the CoopMAC protocol is less than that of the legacy system, therefore reducing total energy radiated to the network. Due to the lower background interference, the sustainable regions for all four rates supported by IEEE 802.llg are extended [15].

IMPLEMENTATION

In order to further validate the design of CoopMAC and demonstrate the feasibility of an incremental deployment, we have made efforts to implement the CoopMAC protocol using off-the-shelf IEEE 802.1 lb network interface cards (NICs) on a Linux platform [15]. Since no existing hardware can perform the receiver-combining function, only the CoopMAC protocol without diversity combining can be implemented. In fact, due to the constraint in accessing the firmware on the chip, we had to take an emulation approach at the driver level for the CoopMAC version without receiver combining, which unfortunately incurs additional protocol overhead. Nevertheless, as demonstrated in the experiment, CoopMAC can still reduce the aver-

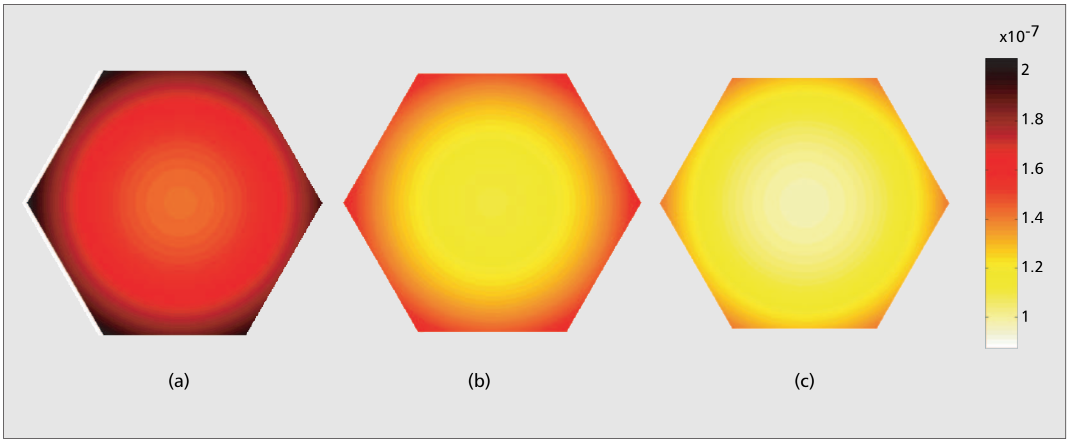


Figure 6. *Interference (W): frequency reuse factor = 3, traffic = 500 p/s, transmission power = l µW: a) 802.11g; b) CoopMAC without receiver combining; and c) CoopMAC with receiver combining.*

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age file-transfer times significantly below the original value, and a more significant performance improvement can be achieved when the entire CoopMAC without receiver combining is completely implemented in firmware. In addition, an *even higher* performance gain would be possible if the CoopMAC with receiver combining can be realized in a baseband chip.

CONCLUSION AND FUTURE WORK

By introducing collaboration from nodes that otherwise do not directly participate in transmission, cooperative communication introduces a new paradigm for wireless communication. It enables a tremendous improvements in robustness, throughput, and delay; a significant reduction in interference; and an extension of coverage range. To fully leverage the concept of cooperation, the entire protocol stack — from physical layer to networking protocols — should be carefully reengineered or even redesigned.

To illustrate the necessity of a cross-layer design approach, we have explored cooperation at both layers 1 and 2 of the OSI protocol stack, and have proposed a new MAC protocol for IEEE 802.11 networks which we call CoopMAC. In particular, the CoopMAC protocol has an option to enable the capability of diversity combining at the receiver, where two versions of the same data are jointly decoded to recover the original packet. As verified by extensive simulations, the CoopMAC protocol, both with and without receiver-combining capability, can achieve substantial performance improvements, without incurring appreciable additional complexity in system implementation. Compared with the noncombining version, the CoopMAC protocol with receiver-combining capability pushes cooperation to an even higher level and reaps additional benefits.

To further exploit cooperation gains at the network layer for highly adaptive and scalable ad hoc networks, many research challenges remain. Given the increasing number of cooperating nodes listening to each transmission, packet forwarding can now be done in a more opportunistic way than has been traditionally considered in ad hoc networks. Indeed, the notions of routing and routing protocols may change when cooperation is fully integrated in the link layer. Cooperative partners should be carefully selected along the route so that optimality at both the link and path levels can be accomplished, while spatial reuse in ad hoc networks is not compromised. Similar subtle cross-layer design issues abound in ad hoc networks, and the implications of node cooperation, including cooperative routing algorithms and the scalability of network capacity with the number of nodes in a network, deserve further investigation.

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BIOGRAPHIES

PEL LIU [S'01] (pliu@photon.poly.edu) completed his B.S. and M.S. degrees in electrical engineering at Xi'an Jiaotong University, China, in 1997 and 2000, respectively. He is a Ph.D. candidate in the Department of Electrical and Computer Engineering of Polytechnic University, Brooklyn, NY. His research interests are in wireless communications and wireless networks.

ZHIFENG TAO [S'00] (jeff.tao@ photon.poly.edu) received a B.E. degree in communication and information engineering from Xi'an Jiaotong University, P. R. China, in 2000. Since then, he has been a Ph.D. candidate in the Department of Electrical and Computer Engineering at Polytechnic University. He also received his M.S. degree in telecommunication networking from Polytechnic University in May 2002. His current research interests include wireless networking, medium access control, quality of service, and cooperative communications.

ZINAN LIN [S'00] (zlin03@utopia.poly.edu) received a B.E degree in information engineering from Zhejiang University, Hangzhou, China, in 1998, and an M.E. degree in electrical engineering from Nanyang Technological University (NTU), Singapore, in 2001. From 1998 to 2000 she was awarded a research scholarship by NTU and worked as a research assistant in the Center for Signal Processing, School of Electronic and Electrical Engineering, NTU. Since 2001, she has been Ph.D. candidate in the Department of Electrical and Computer Engineering, Polytechnic University, Brooklyn, NY. Her general research interests include wireless communications and digital signal processing, especially channel coding, diversity techniques, and CDMA sequence design.

ELZA ERKIP [S'93, M'96, SM'05] (e1za@poly.edu) received M.S. and Ph.D. degrees in electrical engineering from Stanford University in 1993 and 1996, respectively, and a B.S. degree in electrical and electronic engineering from Middle East Technical University, Turkey, in 1990. She joined Polytechnic University in Spring 2000, where she is currently an associate professor of electrical and computer engineering. During 1996–1999 she was with the Department of Electrical and Computer Engineering of Rice University. She received the 2004 Communications Society Stephen O. Rice Paper Prize in the field of communications theory, the NSF CAREER award in 2001, and the IBM Faculty Partnership Award in 2000. She is the Technical Program Co-Chair of the 2006 Communication Theory Workshop. She is also an Associate Editor of *IEEE Transactions on Communications* and a Publications Editor for *IEEE Transactions on Information Theory*. Her research interests are in wireless communications, information theory, and communication theory.

SHIVENDRA S. PANWAR [S'82, M'85, SM'00] (panwar@catt.poly.edu) received a B.Tech. degree in electrical engineering from the Indian Institute of Technology, Kanpur, in 1981, and M.S. and Ph.D. degrees in electrical and computer engineering from the University of Massachusetts, Amherst, in 1983 and 1986, respectively. He joined the Department of Electrical Engineering at the Polytechnic Institute of New York, Brooklyn, NY (now Polytechnic University), where he is a professor in the Electrical and Computer Engineering Department. Currently he is the director of the New York State Center for Advanced Technology in Telecommunications (CATT). He spent the summer of 1987 as a visiting scientist at the IBM T. J. Watson Research Center, Yorktown Heights, NY, and was a consultant to AT& T Bell Laboratories, Holmdel, NJ. His research interests include the performance analysis and design of networks. Current work includes video systems over peer-to-peer networks, switch performance, and wireless networks. He has served as Secretary of the Technical Affairs Council of the IEEE Communications Society (1992–1993) and is a member of the Technical Committee on Computer Communications. He is a co-editor of two books, *Network Management and Control*, Vol. II, and *Multimedia Communications and Video Coding* (Plenum, 1994 and 1996, respectively), and co-author of *TCP/IP Essentials: A Lab-Based Approach* (Cambridge University Press, 2004). He is a co-recipient of the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems.