Link-Layer-and-Above Diversity in Multihop Wireless Networks

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ABSTRACT

The instability of wireless channels was a haunting issue in communications until recent exploration in utilizing variation. The same transmission might present significantly, and usually independently, different reception quality when broadcast to receivers at different locations. In addition, the same stationary receiver might experience drastic fluctuation over time as well. The combination of link-quality variation with the broadcasting nature of the wireless channel itself disclosed a direction in the research of wireless networking, namely, the utilization of diversity. In this article, we summarize the causes of channel diversity in wireless communications, and how it is perceived in different layers of multihop wireless networks. To promote new research innovations in this area, we concentrate on link-layer diversity and speculate on the challenges and potential of diversity schemes at the network layer.

INTRODUCTION

A multihop wireless network, mobile or stationary, poses a challenge in network protocol design. In particular, the error-prone communication links and the unstable network structure are two of the most critical aspects in networking. Numerous efforts have been exerted to address these issues so that a multihop wireless network could be *as good as* a wireline network. In contrast, interest is increasing in utilizing a wireless communication channel by harnessing its broadcasting nature directly. Indeed, it is this nature that separates wireless networks from the rest, and no requirement exists to turn wireless links into wired lines. Only by a direct approach can we make full use of these networks and make wireless networks *better than* wireline networks. Any real-world operating environment of a multihop wireless network inevitably causes different levels of variation in link quality. One salient feature of such random fluctuation is its finer time granularity when compared to the response of a global (end-to-end) solution. Therefore, this is an issue that is unique to this type of network, and localized and dynamic cooperation among relaying nodes opens up a way for us to address this issue. In this article, we speculate on the problem of how to utilize channel diversity at the link layer and above. By reviewing the typical approaches in the literature and focusing on two recent explorations, we investigate the challenges involved and describe-existing solutions.

DIVERSITY IN WIRELESS NETWORKING

Diversity in wireless networking, sometimes called *channel diversity* or *link diversity*, refers to the phenomenon where transmissions at different channels, for example, frequency band, time slot, and so on, possess different reception conditions. A diversity scheme utilizes such a phenomenon for more reliable transmission. Fundamentally, the complex of electro-magnetic wave propagation generally can be attributed to such mechanisms as reflection, diffraction, and scattering.

Considering the basis, treatments, and effective scope, we review the primary forms of diversity schemes in wireless communications as follows: at the physical layer (the first three), at the link layer (the fourth), and a network-layer effect (the last).

Time Diversity — A wireless communication system inevitably is operated in a dynamic environment due to the mobility of both the transceiving parties and any obstacle. Thus, the channel gain is a stochastic process centered at a mean value. That is, instances of transmission at different times may have significantly varying levels of attenuation even if the transmitter and receiver are both stationary. At the extreme, such variance can be observed even within a single transmission. To combat this, identical messages can be transmitted multiple times for better robustness. Alternatively, forward error correction (FEC) coding can be used to spread information over a longer period of transmission time. This is the first form of channel diversity utilized in communications.

Frequency Diversity — Propagation of signals at different frequencies experience differences in reflection, diffraction, and scattering, even at the same time and location. Therefore, practically

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any wireless channel is affected by *frequency-selective fading*, that is, channel gain varying with frequency. Countermeasures to this include simultaneous transmission over multiple subcarriers (e. g., orthogonal frequency division multiplexing [OFDM]) and spreading information in a wider frequency band (e. g., direct sequence-code division multiple access [DS-CDMA]).

Space Diversity — Typically, between a transmitter and a receiver, there are multiple paths for the signal to propagate, whether there is a line-of-sight (LOS) component or not. In addition, the composition of these propagation paths relies on the exact positions of the transmitter, receiver, and all obstacles. Thus, a small change of the position of any of them can vary the channel gain significantly, which is *small-scale fading* in the spatial sense. In contrast, time diversity is a temporal sense of small-scale fading. To utilize space diversity, we can employ multiple transmitters (i.e., transmitter diversity) or multiple receivers (i.e., receiver diversity) for joint transmission of the same message. Multiple-input and multiple-output (MIMO) and space-time coding (STC) are examples using this technique. Depending on the distances among the transmitters or those among the receivers, relative to the wave length of the signal carrier, space diversity can be further classified as *microdiversity* and *macrodiversity*.

Multi-User Diversity — In a wireless network of multiple downlinks or multiple uplinks, or multiple transmitter-receiver pairs in general, scheduling and channel selection can be executed such that the users of the "best instances" are favored to best exploit the channel variation. Thus, the overall system throughput increases with the number of users and channel gain variance. A consequence of utilizing multi-user diversity is that the interface queues are not first-in-first-out (FIFO) any more.

Multipath Diversity — In a multihop wireless network, a given pair of source and destination can be connected through multiple (network-layer sense) paths in the network. The properties of these paths vary in many ways, such as hop length, bandwidth, total delay, queuing delay, expected transmission count, and so on. They are further induced and synthesized from the diversity of the links among these paths. In general, multipath diversity bears a global notion, and it takes the network a longer time to react.

Perception of channel diversity can be made at the physical, data link, and network layers. As we have noted, time diversity, frequency diversity, and space diversity are physical layer notions; multi-user diversity is a link layer one; whereas multipath diversity is a network-wide effect. Thus, diversity as a scheme for data transportation can work at any one or at a combination of these layers.

Physical layer diversity schemes are specific for different causes and thus, usually are addressed more directly. Due to the relatively simple solutions, time and frequency diversity schemes were adopted widely. In contrast, space diversity, especially at the macro level, only recently attracted an increasing number of research activities, collectively referred to as *cooperative communication* [1]. A major reason behind this thrust is the enhancement of the digital signal-processing capabilities that mobile devices possess. At the link layer, link variation usually is induced by historical transmission statistics on the sender side or collected and fed back from the receiver side. A link-layer diversity scheme typically takes measures by regulating link-layer behaviors, for example, parameters for medium-sharing control. An advantage of link-layer diversity is its lower requirement for hardware capabilities. On the other hand, its inductive nature can make it less responsive and timely in decision making. At the network layer, where network-wide routes are accounted, a path metric is always a cumulative quantity and thus takes a longer time to collect and respond to. In addition, these quantities are changing dynamically with the composite link metrics. Therefore, it is generally perceived to be difficult to utilize multipath diversity in multihop networks lacking global information and central control authority, even though potentially, it can help us to improve network performance.

As a result, in this article, we focus on link-layer efforts — and through more explorative endeavors, on others, higher and above, based on the link layer — in exploiting channel diversity in the quest for diversity.

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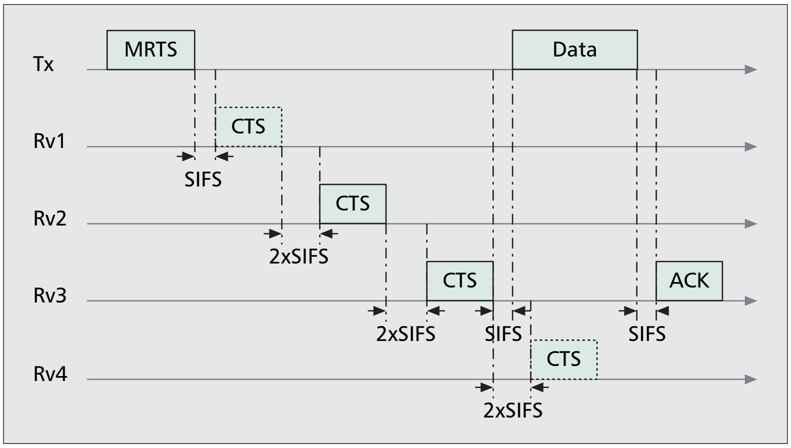
Link-Layer Diversity in Multihop Wireless Networks

Here, we summarize existing link-layer diversity schemes in wireless networks. Because they were proposed in differing contexts, they may carry different names in the literature, such as selection diversity, multicast/group request-to-send (RTS), opportunistic scheduling, link-layer anycast, and so on.

Multi-user diversity first was addressed as a link-layer scheduling scheme by Knopp and Humblet [2] in cellular communication networks and later, was incorporated in CDMA systems. In such centralized systems, the channel-quality information is fed back from users in the cell through an uplink so that the base station can schedule transmissions to the favored users accordingly. In a multihop wireless network, where there is usually no central control authority at the link layer, it requires effective and efficient distributed coordination in transmission. Larsson [3] proposes an innovative handshake and selection diversity forwarding (SDF) to implement downstream forwarder selection in a multihop wireless network, where multiple paths are made available by the routing agent. In this case, a sender in the network dynamically can choose from a set of usable downstream neighbors that presents the lowest transient cost in forwarding the packet. For the sender to make the decision, the IEEE 802.11 distributed coordination function (DCF)-based DATA/ACK handshake is enhanced in two aspects. First, the receiver address (RA) field in the DATA frame is augmented to contain all eligible downstream neighbors. After the reception of DATA, these



■ **Figure 1.** *MRTS in as in [5].*

neighbors each respond with an ACK in the order prescribed by the RA field, interleaved by the short interframe space (SIFS) to avoid interruption. The ACK frame in this case also carries additional information such as link quality and queue length. Second, after collecting the ACKs from the downstream neighbors and selecting the best neighbor as forwarder, the sender transmits a forwarding order (FO) frame, addressed to that neighbor, which in turn responds with a forwarding order ACK (FOA) to confirm the order. Such a four-way handshake is the first explorative link-layer diversity scheme in multihop wireless networks.

Recently, the exploration of link-layer diversity in multihop wireless networks has attracted considerable research attention. In addition to multi-user diversity, it also was used to address such issues as head-of-line (HOL) blocking and opportunistic rate adaptation. These proposals are built upon the RTS/clear-to-send(CTS)/DATA/ACK four-way handshake of IEEE 802.11, given its predominance and availability in the area of multihop wireless networking, and are collectively referred to as multicast RTS (MRTS). Larsson and Johansson [4] refine SDF to accommodate packet forwarding for multiple flows in the network in their proposal of multi-user diversity forwarding (MDF). In MDF, a combination of data rate, forwarder, and flow is considered in the selection by the sender, thus the non-FIFO queuing. The implementation also adopts a preceding placement of the control frames that is more 802.11-compliant, as opposed to the trailing placement in SDF. Jain and Das [5] design a *link-layer anycast* to implement multipath routing, faithfully based on the IEEE 802.11 specifications. This is achieved by augmenting the standard RTS frame to MRTS that contains multiple RAs to poll them. Upon the reception of MRTS, the ith polled node backs off by $(2i - 1) \times T_{SIFS} + (i - 1) \times T_{CTS}$ before transmitting a CTS. After the sender has received a CTS, it unicasts a DATA frame after time SIFS (T_{SIFS}), a shorter time than what the next CTS requires to back off, to interrupt any additional CTSs from subsequent receivers. The receiver of DATA acknowledges it with an ACK after T_{SIFS} as well. Figure 1 provides an example of how it works. In the scenario, one node (Tx) has four downstream neighbors: Rv_1, Rv_2, Rv_3, and Rv_4. Assume that the MRTS is intended for all neighbors but was received correctly only by Rv_2, Rv_3, and Rv_4. After $3T_{SIFS} + T_{CTS}$, Rv_2 replies with a CTS that is garbled when Tx receives it. After $5T_{SIFS}$ + 2TCTS, Rv_3 replies with a CTS. After correct reception and a back off of T_{SIFS}, Tx transmits DATA. This cancels the CTS reply from Rv_4. The transmission is completed by the Rv_4 ACK after T_{SIFS} receives DATA. In a simultaneous investigation, Wang, Zhai, and Fang [6] specify an opportunistic packet scheduling and media-access control (OSMA) protocol to address the HOL blocking problem. HOL blocking occurs when the frame that is currently at the head of the interface queue at the sender's link layer cannot be transmitted successfully, for example, due to the temporary unavailability of the receiver. One salient feature of this protocol is the shorter back-off time of CTS transmission as a result of receiver-carrier-sensing capability. Thus, after the reception of MRTS, the ith polled receiver backs off by a shorter time of $T_{SIFS} + (i - 1) \times T_{slot}$ before transmitting a CTS. In this proposal, only one CTS is in fact transmitted, that is, by the first receiver in the ordered list that is able to respond; all remaining receivers yield to the upcoming DATA frame despite the fact that it may have received the MRTS successfully. In the context of rate adaptation in wireless LANs, Ji et al. [7] present an MRTS-based opportunistic scheduling with packet concatenation, called medium-access diversity (MAD). In MAD, when a high data rate is selected by the access point (AP), the AP can concatenate multiple frames into a longer DATA frame that lasts for approximately the same duration of sending a single frame at the basic rate. This effectively brings down the overhead-to-payload ratio at the link layer. On the other hand, the polling time in MAD is longer because the AP must wait for $n \times (T_{CTS} + T_{SIFS}) + T_{SIFS}$ before it transmits the DATA frame, where n is the number of receiver addresses in the MRTS. Zhang, Chen, and Marsic [8] improve MRTS to address HOL blocking by further reducing its operation overhead. In particular, a sender intelligently composes a shorter list of receivers for the MRTS using a learning module. The learning module selects a subset of the eligible downstream nodes that has the least correlation in channel condition, based on its recorded transmission history. A shorter list, and thus a smaller overhead, is shown to have the same likelihood of having at least one receiver available as a list that includes all eligible nodes. This approach is more efficient than the somewhat "blind" inclusion of all eligible receivers and thus, carries the exploitation of link-layer diversity one step further.

EFFICIENT COORDINATION

The implementation of link-layer diversity for the layer above the physical layer requires more sophisticated and efficient coordination. It is particularly challenging for multihop wireless networks that are void of centralized control authorities. Multi-user diversity, as a form of link layer diversity, is effective and became feasible because cell base stations can provide central intelligence and control. In contrast, a multihop wireless network operates in a more flexible setting, which introduces an entire spectrum of networking issues. The most predominant medium access control (MAC) for such networks is the IEEE 802.11 DCF. This type of MAC protocol essentially is a carrier-sensing multiple access with collision avoidance (CSMA/CA) scheme. IEEE 802.11-based networks usually operate with a simple two-way handshake of DATA/ACK frames between the sender and receiver. The optional RTS/CTS control frames are used to precede a DATA/ACK to address the *hidden terminal problem*, where two transmitters are out of carrier-sensing range of each other. The reason that such a four-way handshake usually is not preferred is its high overhead. Although these optional frames are short, they must be transmitted at the basic data rate to be robust. On the other hand, the physical layer module of an 802.11-compliant device is capable of transmitting the DATA frame at different data rates using different coding and modulation schemes, with the highest being many times faster than the basic rate. As a result, these control frames, along with the inter-frame spaces, impose a significant amount of communication overhead. The higher the data rate used to transmit the DATA frame, the lower the payload-to-overhead ratio is. Observe that all the MRTS-based link-diversity schemes are in fact extending the optional RTS/CTS to a mandatory poll-and-select paradigm. Despite their very explorative nature, these MRTS-based protocols should be further improved for better system performance.

Of course, this is easier said than done. In a unicast routing protocol for multihop wireless networks, a sequence of relaying nodes are enlisted by the routing module to forward the packet. A multipath routing protocol makes multiple paths available for a given pair of source and destination, mostly for better utilization of link-layer diversity. However, any given packet still follows a single path among these candidate paths though this type of path can vary from packet to packet for the same source-destination pair. The challenge is to ensure that a packet is forwarded by exactly one of the five eligible downstream relaying nodes with a minimum of extra system overhead. In addition, the original function of link-layer reliability still should be guaranteed. Link-layer diversity is built on the broadcasting nature of wireless channels. Thus, any eligible relay (e. g., as prescribed by the routing module) with good transient channel quality could potentially forward the packet. Without poll-and-select, the multitude of the relays with good channel conditions must coordinate with each other such that exactly one of them forwards the packet. And this is to be accomplished without introducing additional control frames. Apparently, this is looking one layer up, to the network layer, for help.

LINK LAYER AND ABOVE

When seeking diversity above the link layer, it is critical that the solution be sufficiently agile in response to the very fine time granularity of link variation. Thus, a dynamic and localized cooperation mechanism is imperative. The coordination at link layer and above was studied in a few different ways recently. We review Ex opportunistic routing (ExOR) [9] and [10] and two examples of innovation in quest for network performance. ExOR is a cross-layer protocol and blends the scheduling functionality of the link layer with the route selection functionality of the network layer. BEND is a lightweight link-layer solution that peeks at network layer information in its diversity-driven forwarder selection.

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EXOR: CROSS-LAYER OPPORTUNISTIC FORWARDING

ExOR is an explorative cross-layer opportunistic forwarding technique in multihop wireless networks by Biswas and Morris. It fuses the MAC and network layers so that the MAC layer can determine the actual next-hop forwarder *after* transmission depending on the transient channel conditions at all eligible downstream nodes. Nodes are enabled to overhear all packets transmitted in the channel, whether intended for it or not. A multitude of forwarders can potentially forward a packet as long as it is included on the forwarder list carried by the packet. Thus, if a packet is heard by a listed forwarder closer to the destination with a good reception condition, this long-haul transmission should be utilized. Otherwise, shorter and thus more robust transmissions always can be used to guarantee reliable progress. The challenge is to ensure that exactly one of the listed forwarders relays the packet that is likely to be the closest to the destination at the same time. This is addressed by prioritized scheduling among the listed forwarders according to their distance to the destination. ExOR was tested on a 38-node mesh testbed, called MIT Roofnet, and shows significant performance gain compared to conventional packet transportation.

Route calculation in ExOR is essentially link-state-based source routing, where every node has global topology information. Each link between a node pair is associated with a quasi-static weight. Based on the cost of the links, each node executes a shortest path algorithm to obtain the "distances" to all other nodes in the network. The distance information is utilized later by a node as source to determine the priorities among intermediate nodes in helping to forward packets to a destination. ExOR operates in batches, where a set of packets from the source are processed collectively and cooperatively en route to achieve a small amortized per-packet overhead. For a given batch, 90 percent of packets are transported by opportunistic forwarding; whereas the remaining 10 percent are transported using conventional routing to clean up. In ExOR, the six MAC and network layers are tightly coupled, in that the forwarders as routing entities participate in packet scheduling directly. A higher-priority node in a batch backs off by a shorter delay than a lower-priority node before transmitting what it has overheard for the batch. Whenever a packet is forwarded, it carries a *batch map*. This map describes, for each packet in the

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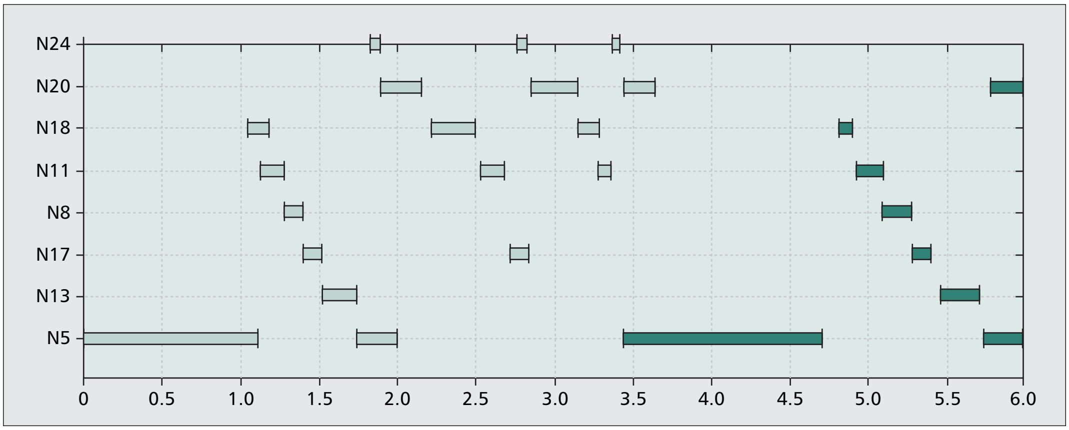


■ **Figure 2.** *ExOR.*

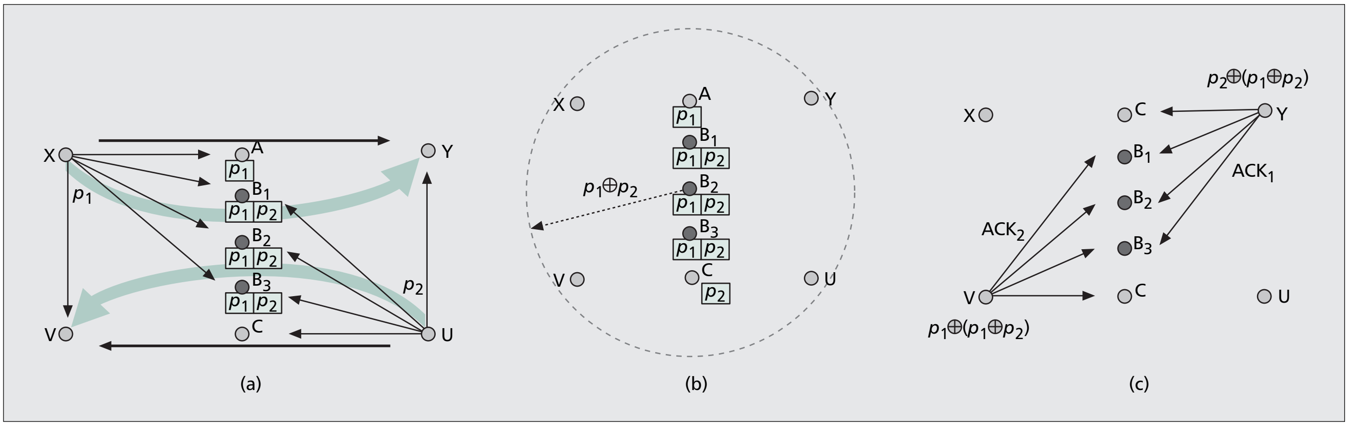
same batch, the highest-priority forwarder that this packet has reached, as a progress indicator, to the best of the forwarder's knowledge. Whenever a packet is overheard by a listed forwarder, its batch map is used to update the forwarder. Consequently, forwarding a packet downstream also serves as acknowledgment upstream. Figure 2 [9] depicts a timeline for transporting a batch of packets, followed by a partial second batch using opportunistic forwarding. In this scenario, node N_5 has packets to send to N_{24}. Nodes N_{24}, N_{20}, N_{18}, N_{11}, N_8, N_{17}, and N_{13} are the forwarders listed by the source N_5, as indicated by their relative positions on the y-axis. The complete first batch is indicated by the bars with a lighter shade and the partial second batch by the darker shade. The horizontal length of each bar corresponds to the number of packets transmitted by the node. At the beginning, node N_5 transmits the entire batch, some of which can reach as far as node N_{18}, with others falling short at closer nodes. Each of these forwarders relays packets that it has overheard but that have not been relayed by a higher-priority forwarder in the order dictated by the forwarder list. It takes node N_{24} three acknowledgments, that is, about 3.5 seconds, to finish transporting 90 percent of the batch. The remaining are forwarded using conventional routing, which is not depicted in the figure.

ExOR is more efficient overall than any of the MRTS-like protocols, not only because it does not use any additional control frames but also because the acknowledgment is piggybacked by the batch map carried by DATA frames. In this sense it is very innovative and has been shown to be very effective in a practical sense. To implement it, the packets must carry the forwarder list and batch map, which introduces communication overhead. When the network becomes large, this overhead inevitably increases to provide a full path with sufficient redundancy. After all, it is a source-routing protocol. In addition, the timing in delaying forwarding packets among the listed forwarder should be carefully engineered, which can be particularly hard in channels with significant variation. That said, it is even harder for a network to accommodate multiple simultaneous flows. Its cross-layer scheme gives the designer much more control to implement the above, but also blurs the boundary between the link and network layers. As a result, it will be hard to use ExOR in different device platforms. Nevertheless, ExOR is a definite eye-opener for a new communication paradigm in multihop wireless networks.

BEND — Proactive Packet Mixing

BEND is a MAC layer solution to practical network coding, originally proposed by Zhang, Chen, and Marsic to enhance the likelihood of the coding of packets in different flows in the proximity of a multihop wireless network. It is an exploration of the broadcasting nature of wireless channels to proactively capture more coding opportunities. In BEND, any node can code and forward a packet even when the node is not the intended MAC receiver of the packet if the node senses that in doing so it can lead the packet to its ultimate destination. Essentially, BEND considers the union of all of the interface queue contents at the nodes within a neighborhood, that is, a "neighborhood" coding repository; whereas traditional mixing methods only process "individual" coding repositories at separate nodes. Moreover, BEND is designed such that, if there is no network coding possible among multiple flows, it still can use multiple helping forwarders to utilize link-layer diversity effectively. It is light-weight, IEEE 802.11-compliant, and can support different routing protocols. It works because the ray of light bends in the presence of a gravitational field and thus, derives its name.

The basic operation of BEND is illustrated by a simple example in Fig. 3 although BEND works under more general conditions. In Fig. 3a, node X has packet p_1 for node Y that is two hops away, and U has p_2 for V, also two hops away. The forwarders determined by the routing protocol are nodes A and C, respectively. We assume that three other nodes, B_1, B_2, and B_3, are also in the range of X, Y, U, and V. When a packet, for example, p_1 or p_2, is handed from the network layer down to the MAC layer, its header is enhanced to include not only the address of the next-hop node but also that of the following-hop node. Such information can be obtained from the routing module. After the packets, p_1 of node X and p_2 of node



■ **Figure 3.** *BEND.*

U are transmitted, p_1 is received by nodes A (intended forwarder), B_1, B_2, B_3, and V, and p_2 is received by B_1, B_2, B_3, C (intended forwarder), and Y. Packet p_1 is placed in the queues of nodes A, B_1, B_2, and B_3 because they are all neighbors of the p1 second-next hop (node Y) as indicated by the packet header. It is, otherwise, buffered by V for future decoding. Similarly, p_2 is queued at nodes B_1, B_2, B_3, and C and buffered at Y. Nodes B_1, B_2, and B_3 can choose to transmit $p_1 \otimes p_2$ if they determine that the coded packets can be correctly decoded by their second-next-hop neighbors. All of the intermediate nodes A, B_1, B_2, B_3, and C could forward the packet(s) in their queues, coded or not. To expedite the packet forwarding, coded packets are transmitted with a higher priority without starving uncoded packets. This is achieved by assigning a different back-off time to forwarders. Assume that node B_2 wins the channel and transmits $p_1 \otimes p_2$ (Fig. 3b). The second-next-hop nodes V and Y receive the XORed packets and are able to decode them using the packets stored in their buffers. Then, they reply instantly with an ACK in a "distributed bursty" way in the order specified by the enhanced MAC header, separated by a SIFS. Such a reliable link-layer broadcasting mechanism also helps to remove the packets queued at the intermediate nodes to avoid packet duplication (Fig. 3c). When no coding is applicable, any intermediate node that has a good channel condition to receive the packet can forward it to the second-next hop opportunistically. Because all helpers are neighbors of the sender, it is likely they are within carrier-sensing range of each other. As a result, the CSMA-CA mechanism plus the trailing ACK can ensure that exactly one of them forwards the packet.

BEND was tested using computer simulation with a lossy physical-layer model and displays superb capabilities, simultaneously in traffic mixing for network coding when applicable, and in traffic dispersing for link diversity without network coding. The need for traffic concentration for network coding and the need for traffic separation to approximate the network capacity were in conflict until the BEND solution. Because the selection of a forwarder is a per-hop and per-flow decision, BEND is especially suitable for link-layer diversity. With a clear separation between the MAC and network layers, it can be ported easily to support a wide spectrum of routing protocols. On the other hand, being a completely link-layer solution, its current design is limited to two hops in forwarding assistance, and its extension to more hops has yet to be explored.

Conclusion

In wireless networking research, the focus is switching from making wireless channels as good as wireline channels to direct utilization of some of the inherent characteristics of wireless channels. Channel diversity is one such example. Although it can be perceived as a physical data link, or network 8 layer effect, it reveals more potential to further boost the performance of multihop wireless networks at the link layer and above. A challenge, as well as an opportunity, in doing so is the stringent requirement of dynamic and localized response mechanisms because of the finer time granularity than that which a traditional end-to-end solution can effect. Yet, as we have noticed, a link-layer-and-above scheme has indicated possibilities of further performance improvement despite its difficulty and overhead in implementation. Nevertheless, this opens up a new vision in exploration of channel diversity. For example, when reception diversity is studied as one way to look at the problem, can interference diversity also be investigated? That is, the interference level also can vary across a short distance or over a short period of time and as a result, the carrier-sensing behavior of transmitting nodes also presents diversity. Are they two sides of the same coin, or will it introduce new issues? Either for reception or interference diversity, there is always (positive or negative) correlation among links in a neighborhood. Is this something we can rely on for decision making? One step ahead, when power control is carefully exercised, multiple transmissions can happen simultaneously without interfering with each other. The space and frequency distribution of such parallel flows will change over time. Efficient coordination to enable this to occur will be beneficial but complex. How do we approach this? We will see for ourselves.

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Biographies

Biographies of the authors were not available when this issue went to press.