

WiLDNet: Design and Implementation of High Performance WiFi Based Long Distance Networks *

Rabin Patra^{† ‡} Sergiu Nedeveschi^{† ‡} Sonesh Surana[†] Anmol Sheth[§]
Lakshminarayanan Subramanian[¶] Eric Brewer^{† ‡}

Abstract

WiFi-based Long Distance (WiLD) networks with links as long as 50–100 km have the potential to provide connectivity at substantially lower costs than traditional approaches. However, real-world deployments of such networks yield very poor end-to-end performance. First, the current 802.11 MAC protocol has fundamental shortcomings when used over long distances. Second, WiLD networks can exhibit high and variable loss characteristics, thereby severely limiting end-to-end throughput.

This paper describes the design, implementation and evaluation of WiLDNet, a system that overcomes these two problems and provides enhanced end-to-end performance in WiLD networks. To address the protocol shortcomings, WiLDNet makes several essential changes to the 802.11 MAC protocol, but continues to exploit standard (low-cost) WiFi network cards. To better handle losses and improve link utilization, WiLDNet uses an adaptive loss-recovery mechanism using FEC and bulk acknowledgments. Based on a real-world deployment, WiLDNet provides a 2–5 fold improvement in TCP/UDP throughput (along with significantly reduced loss rates) in comparison to the best throughput achievable by conventional 802.11. WiLDNet can also be configured to adapt to a range of end-to-end performance requirements (bandwidth, delay, loss).

1 Introduction

Many developing regions around the world, especially in rural or remote areas, require low-cost network connectivity solutions. Traditional approaches based on telephone, cellular, satellite or fiber have proved to be an expensive proposition especially in low population density and low-income regions. In Africa, even when cellular or satellite coverage is available in rural regions, bandwidth is extremely expensive (e.g. satellite bandwidth is about US\$3000/Mbps per month) [15]. Cellular and WiMax [25], another proposed solution, require a minimum user density to amortize the cost of the basestation

that is so far too high for rural areas. Finally, all of these solutions focus on licensed spectrum and carrier-based deployment, which limits their usefulness to the kind of “grass roots” projects typical for developing regions.

WiFi-based Long Distance (WiLD) networks [8, 9, 23] are emerging as a low-cost connectivity solution and are increasingly being deployed in developing regions. The primary cost gains arise from the use of low-cost and low-power single-board computers and high-volume low-cost off-the-shelf 802.11 wireless cards using unlicensed spectrum. The nodes are also lightweight and don’t need expensive towers [6]. These networks are very different from the short-range multi-hop urban mesh networks [5]. Unlike mesh networks, which use omnidirectional antennas to cater to short ranges (less than 1–2 km at most), WiLD networks are comprised of point-to-point wireless links that use high-gain directional antennas (e.g. 24 dBi, 8° beam-width) with line of sight (LOS) over long distances (10–100 km).

Despite the promise of WiLD networks as a low-cost network connectivity solution, the real-world deployments of such networks face many challenges [23]. Our experience has shown that in particular, the performance of WiLD networks in real-world deployments is abysmal. There are two main reasons for this poor performance. First, the stock 802.11 protocol has fundamental *protocol shortcomings* that make it ill-suited for WiLD environments. Three specific shortcomings include: (a) the *802.11 link-level recovery* mechanism results in low utilization; (b) at *long distances frequent collisions occur because of the failure of CSMA/CA*; (c) WiLD networks experience *inter-link interference* which introduces the need for synchronizing packet transmissions at each node [17]. The second problem is that the links in our WiLD network deployments (in US, India, Ghana) experienced very *high and variable packet loss rates* induced by external factors (primarily external WiFi interference in our deployment); under such high loss conditions, TCP flows hardly progress and continuously experience timeouts.

In this paper, we describe the design and implementation of WiLDNet, a system that addresses all the aforementioned problems and provides enhanced end-to-end performance in multi-hop WiLD networks. Prior to our study, the only work addressing this problem was

*This work was partly supported by National Science Foundation grant No. 0326582 and Intel Research.

[†]University of California, Berkeley

[‡]Intel Research, Berkeley

[§]University of Colorado, Boulder

[¶]New York University

2P [17], a MAC protocol proposed by Raman *et al.* The 2P design primarily addresses inter-link interference, and proposes a TDMA-style protocol with synchronous node transmissions. The design of WiLDNet leverages and builds on top of 2P, making additional changes to further improve link utilization and to make the system robust to packet loss. The key factors that distinguish WiLDNet from 2P and the stock 802.11 protocol are:

1. *Improving link utilization using bulk acknowledgments:* The current 802.11 protocol uses a stop-and-wait link recovery mechanism, which when used over long distances with high round-trip times leads to under-utilization of the channel. To improve link utilization, WiLDNet uses a bulk packet acknowledgment protocol.

2. *Designing TDMA in lossy environments:* The stock 802.11 CSMA/CA mechanism is inappropriate for WiLD settings since it cannot assess the state of the channel at the receiver. 2P proposed a basic TDMA mechanism (instead of CSMA/CA) that explicitly synchronized transmissions at each node to prevent inter-link interference. However, with high packet loss rates, explicit synchronization can lead to deadlock scenarios due to loss of synchronization marker packets. In WiLDNet, we use an implicit approach, using loose time synchronization among nodes to determine a TDMA schedule that is not affected by packet loss.

3. *Handling high packet loss rates:* In our WiLD network deployments, we found that external WiFi interference is the primary source of packet loss. The emergence of many WiFi deployments, even in developing regions, will exacerbate this problem. In WiLDNet, we use an adaptive loss-recovery mechanism that uses a combination of FEC and bulk acknowledgments to significantly reduce the perceived loss rate and to increase the end-to-end throughput. We show that WiLDNet’s link-layer recovery mechanism is much more efficient than a higher-layer recovery mechanisms such as Snoop [2].

4. *Application-based parameter configuration:* Different applications have varying requirements in terms of bandwidth, loss, delay and jitter. In WiLDNet, configuring the TDMA and recovery parameters (time slot period, FEC, number of retries) provides a tradeoff spectrum across different end-to-end properties. We explore these tradeoffs and show that WiLDNet can be configured to suit a wide range of goals.

We have implemented all our modifications as a *shim layer* above the driver using the Click modular router [11]. We have deployed WiLDNet in our campus testbed of 6 long-distance wireless links. Figure 1 shows the topology of our campus testbed. Apart from the design and implementation of WiLDNet, we have had two years experience in deploying and maintaining two production WiLD networks in India and Ghana that support real users. Our network at the Aravind Eye Hos-

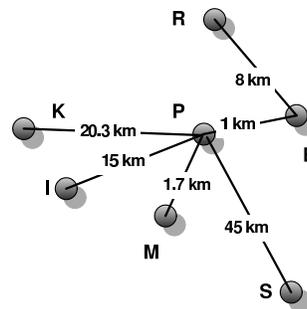


Figure 1: Overview of the WiLD campus testbed (not to scale)

pital, India, provides interactive patient-doctor video-conferencing services between the hospital and five surrounding villages (10–25 km away from the hospital). It is currently being used for about 2000 remote patient examinations per month. The design of WiLDNet that is presented in this paper has continuously evolved in the past two years to solve many of the performance problems that we faced in our deployments.

Using a detailed performance evaluation, we roughly observe a 2–5 fold improvement in the TCP throughput over WiLDNet in comparison to the best achievable TCP throughput obtained by making minor driver changes to the standard 802.11 MAC across a wide variety of settings. On our outdoor testbed, we get upto 5 Mbps of TCP throughput over 3 hops under lossy channel conditions, which is 2.5 times more than that of standard 802.11b. The bandwidth overhead of our loss-recovery mechanisms is minimal. In the near future we intend to transition our system from the campus testbed into the two production networks in India and Ghana.

2 WiLD Performance Issues

In this section, we describe in detail two important causes for poor end-to-end performance in WiLD networks: (a) 802.11 protocol shortcomings; (b) high and variable loss-rates in the underlying channel induced by external factors. We begin by providing a brief description of WiLD networks in Section 2.1. In Section 2.3, we elaborate on three protocol shortcomings of 802.11 in WiLD settings: (a) inefficient link-level recovery; (b) collisions at long distances and (c) inter-link interference. For each of these, we show that just manipulating driver level parameters is insufficient to achieve good performance over long-distance links. Then in Section 2.4, we summarize the results of our study of the loss characteristics in our deployed WiLD networks. We observed the primary cause of these losses to be external WiFi interference and not multi-path effects. Finally, in Section 2.5, we discuss the effect of these two causes on TCP performance.

2.1 WiLD Networks: An Introduction

The IEEE 802.11 standard (WiFi) was designed for wireless broadcast environments with many hosts in close vicinity competing for channel access. Wireless ra-

radios are half-duplex and cannot listen while transmitting; consequently, a CSMA/CA (carrier-sense multiple-access/collision avoidance) mechanism is used to reduce collisions. Unlike standard WiFi networks, WiFi-based Long Distance (WiLD) networks use multi-hop point-to-point links, where each link can be as long as 100 km. To achieve long distances in single point-to-point links, nodes use directional antennas with gains as high as 30dBi, and may use high-power wireless cards with up to 400mW of transmit power. Additionally, in multi-hop settings, nodes have multiple radios with one radio per fixed point-to-point link to each neighbor. Each radio can operate on different channels if required. This is different from standard 802.11 networks where nodes route traffic through an access point and contend for the medium on a single channel. Some real life deployments of WiLD networks include the Akshaya network [24], the Digital Gangetic Plains project [4], and the CRCnet project [8]. The Akshaya network is one of the largest wireless deployments in the world with over 400 nodes and links going up to 30 km.

2.2 Experimental Setup

We use three different experimental setups to conduct measurements and to evaluate WiLDNet.

Campus testbed: Figure 1 is our real-world campus testbed on which we have currently deployed WiLDNet. The campus testbed consists of links ranging from 1 to 45 km, with end points located in areas with varying levels of external WiFi interference. We also use one of the links in our Ghana network (65km).

Wireless Channel Emulator: The channel emulator (Spirent 5500 [21]) enables repeatable experiments by keeping the link conditions stable for the duration of the experiment. Moreover, by introducing specific propagation delays we can emulate very long links and hence study the effect of long propagation delays. We can also study this in isolation of external interference by placing the end host radios in RF isolation boxes.

Indoor multi-hop testbed: We perform controlled multi-hop experiments on an indoor multi-hop testbed consisting of 4 nodes placed in RF isolated boxes. The setup was designed to recreate conditions similar to long outdoor links where transmissions from local radios interfere with each other but simultaneous reception on multiple local radio interfaces is possible. We can also control the amount of external interference by placing an additional wireless node in each isolation box just to transmit packets mimicking a real interferer. The amount of interference is controlled by the rate of the CBR traffic sent by this node. The indoor setup features very small propagation delay on the links; we use it only to perform experiments evaluating TDMA scheduling and loss recovery from interference.

We use Atheros 802.11 a/b/g radios for all our experiments. The wireless nodes are 266 MHz x86 Geode single board computers running Linux 2.4.26. The choice of this hardware platform is motivated by the low cost (\$140) and the low power consumption (< 5W). We use *iperf* to measure UDP and TCP throughput. The madwifi Atheros driver was modified to collect relevant PHY and MAC layer information.

2.3 802.11 Protocol Shortcomings

In this section, we study the three main limitations of the 802.11 protocol: the inefficient link-layer recovery mechanism, collisions in long-distance links, and inter-link interference. These limitations make 802.11 ill-suited even in the case of a single WiLD link. Based on extensive experiments, we also show that modifying the driver-level parameters of 802.11 is insufficient to achieve good performance.

2.3.1 Inefficient Link-Layer Recovery

The 802.11 MAC uses a simple stop-and-wait protocol, with each packet independently acknowledged. Upon successfully receiving a packet, the receiver node is required to send an acknowledgment within a tight time bound (ACKTimeout), or the sender has to retransmit. This mechanism has two drawbacks:

- As the link distance increases, propagation delay increases as well, and the sender waits for a longer time for the ACK to return. This decreases channel utilization.
- If the time it takes for the ACK to return exceeds the ACKTimeout parameter, the sender will retransmit unnecessarily and waste bandwidth.

We illustrate these problems by performing experiments using the wireless channel emulator. To emulate long distances, we configure the emulator to introduce a delay to emulate links ranging from 0–200 km. Figure 2(a) shows the performance of the 802.11 stop-and-wait link recovery mechanism over increasing link distances. With the MAC-layer ACKs turned off (No ACKs), we achieve a throughput of 7.6 Mbps at the PHY layer data rate of 11 Mbps. When MAC ACKs are enabled, we adjust the ACK timeout as the distance increases. In this case, the sender waits for an ACK after each transmission, and we observe decreasing channel utilization as the propagation delay increases. At 110 km, the propagation delay exceeds the maximum ACK timeout (746 μ s for Atheros, but smaller and fixed for Prism 2.5 chipsets) and the sender always times out before the ACKs can arrive. We notice a sharp decrease in received throughput, as the sender retries to send the packet repeatedly (even though the packets were most likely received), until the maximum number of retries is reached (this happens because, if an ACK is late, it is ignored). This causes the received throughput to stabilize at $BW_{110km}/(no_of_retries + 1)$.

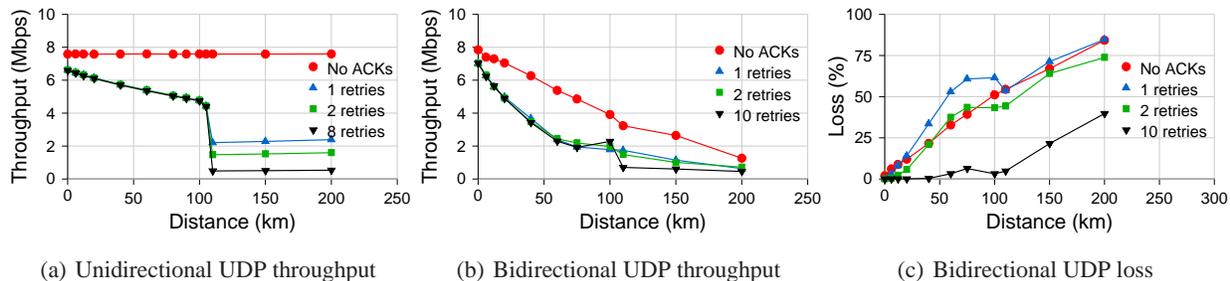


Figure 2: UDP throughputs for standard 802.11 CSMA on single emulated link. ACK timeouts were adjusted with increasing distance (on Atheros cards). Traffic is 1440 byte CBR UDP packets in 802.11b at PHY layer datarate of 11Mbps.

2.3.2 Collisions on long-distance links

The 802.11 protocol uses a CSMA/CA channel-access mechanism, in which nodes listen to the medium for a specified time period (DIFS) before transmitting a packet, thus ensuring that the channel is idle before transmission. This translates to a maximum allowable distance at which collisions can be avoided of about 15km for 802.11b (DIFS is $50\mu s$), 10.2 kms for 802.11a and 8.4km for 802.11g. For longer links it is possible for a node to start transmitting a packet unaware of another packet transmission at the other end. As the propagation delay increases, this probability of loss due to collisions increases.

We illustrate the above-mentioned effect by using a simple experiment: we send bidirectional UDP traffic at the maximum possible sending rate on the emulated link and measure the percentage of packets successfully received at each end. Figure 2(c) shows how the packet loss rate increases with distance. Figure 2(b) shows the sum of the throughputs achieved at both ends for bidirectional UDP traffic as we increase the distance for a link. Note that there are no losses due to attenuation or outside interference in this controlled experiment; all of the losses are due to collisions.

A possible solution to this issue would be to increase the DIFS time interval in order to permit longer propagation delays. However, just as in the case of the ACK timeout, this approach would decrease channel utilization substantially for longer links. Furthermore, we are not aware of any 802.11 chipsets that allow the DIFS interval to be configured.

2.3.3 Multiple Link Interference

Another important source of errors is the interference between adjacent 802.11 links operating in the same channel or in overlapping channels. Although interference between adjacent links can be avoided by using non-overlapping channels, there are numerous reasons that make it advantageous to operate adjacent links on the same frequency channel, as described by Raman *et al.* [17]. Moreover, there are WiLD topologies such as the Akshaya network [24] where different channels can-

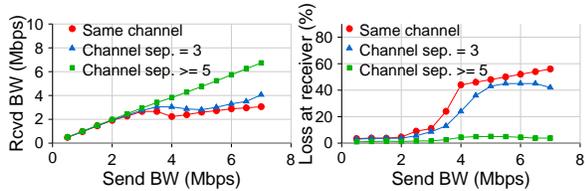
not be allocated to all the pairs of adjacent links, given the high connectivity degree of several nodes.

Inter-link interference occurs because the high-power radios create a strong RF field in the vicinity of the radio, enough to interfere with the receptions at nearby radios. Directional antennas also have sufficiently high gain (4–8 dBi) side lobes [4] in addition to the main lobes.

The first type of problem occurs when multiple radios attached to the same node attempt to transmit at the same time. As soon as one radio starts transmitting after sensing the carrier to be idle, all other radios in the vicinity find the carrier to be busy and backoff. This is desirable in a broadcast network to avoid collisions between two senders at any receiver node. However, in our network where each of these radios transmits over point-to-point long distance links to independent receivers, this back-off leads to suboptimal throughput. A second problem occurs when packets being received at one link collide with packets simultaneously transmitted on some other link on the same node. The signal strength of packets transmitted locally on a node overwhelms any packet reception on other local radios.

In order to illustrate these effects, we perform experiments on the real-world setup presented in Figure 1. First, we attempt to simultaneously transmit UDP packets to both K and M from node P. The total send throughput on both links is 14.20 Mbps when they are on non-overlapping channels (separation ≥ 4) but drops to only 7.88 Mbps when on the same channel. Next we send UDP packets from node M to node K, relayed through node P at different transmitting rates. We then measure received throughput and packet loss rate for various channel spacing between the two adjacent links, as presented in Figures 3(a) and 3(b). We observe that interference does reduce the utilization of the individual links and significantly increases the link loss rate (even in the case of partially overlapping channels).

Therefore, the maximum channel diversity that one can simultaneously use at a single node in the case of 802.11(b) is restricted to 3 (channels 1,6,11) which may not be sufficient for many WiLD networks. This motivates the need for a scheme that allows the efficient



(a) UDP throughput received (b) UDP loss at receiver

Figure 3: Effect of interference on received UDP throughput and error rate when sending from M to K through a relay node, P . Channel separation is no. of channels in 802.11b. Traffic is 1440 byte CBR UDP packets in 802.11b at PHY layer datarate of 11Mbps.

operation of same-channel adjacent links. This can be achieved by using a mechanism similar to the one used in 2P [17], that synchronizes both packet transmission and reception across adjacent links to avoid interference and improve throughput.

2.4 Channel Induced Loss

Apart from protocol shortcomings, another cause for poor performance is high packet loss rates in the underlying channel due to external factors. We refer to these as *channel induced losses*. In this section, we briefly summarize the relevant conclusions from our study (Sheth *et al.* [20]) where we conduct a detailed analysis of loss characterization on our WiLD network deployments.

Loss magnitude and variability: Figure 4 illustrates the loss variation across time on two different links in our testbed. We find that the loss is highly varying with time and there are bursts of high loss of lengths varying from few milliseconds up to several minutes. However on the urban links, there is always a non-zero residual that varies between 1–20%. The residual loss rates in our rural links are negligible. Finally, we found the loss characteristics along a single link to be highly asymmetric. One example is illustrated in Figure 4 where we observe that average loss rate from S to P was lower (10%) than the loss from P to S (20%).

Sources of loss: Our study (Sheth *et al.* [20]) investigates two potential sources for channel losses on WiLD links: external WiFi interference and multipath interference. It finds external WiFi interference to be the dominant source of packet loss and multipath to have a much smaller effect.

Multipath has a small effect because the delay spreads in WiLD environments are an order of magnitude lower than those in mesh networks. This is because as link distances increase, the path delay difference between the primary line-of-sight (LOS) path and secondary reflected paths becomes small enough to avoid inter-symbol interference (ISI). On the other hand, the primary path signal can be significantly attenuated from the secondary paths

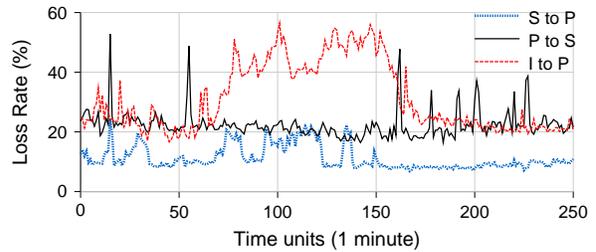


Figure 4: Packet loss variation on 2 links over a period of about 4 hours. Traffic was 1Mbps CBR UDP packets of 1440 bytes each at a PHY datarate of 11Mbps in 802.11b.

that undergo a phase shift of 180° after reflection. This is verified by our measurements [20] where we see that all our long-distance links in rural areas have very low loss. In comparison, an urban mesh network deployment (like Roofnet) has many short, non line-of-sight links and thus loss from ISI is a much bigger problem.

However if WiLD links are deployed in the presence of external interfering sources, the hidden terminal problem can be much worse than in the case of an urban mesh network (with omnidirectional antennas). Due to the highly directional nature of the transmission, a larger fraction of interfering sources within range of the receiver act as hidden terminals since they cannot sense the sender’s transmissions. In addition, due to long propagation delays, even sources within the range of a directional transmitter can interfere by detecting the conflict too late. Measurements on our outdoor testbed links and indoor testbed demonstrate a strong correlation between loss and volume of traffic from external sources on the same or adjacent channels [20].

This is different from the case of WiFi mesh networks like Roofnet [1], for which the authors concluded that multipath interference was a significant source of packet loss, while WiFi interference was not.

Other factors: Measurements on our testbed show that there is no measurable non-WiFi interference in our urban links [20]. This is indicated by the absence of significant correlation between noise floor (reported by the wireless card) and loss rates. Also, the loss rates on different channels are not correlated to each other implying the absence of any wide-band interfering noise. Experiments with different 802.11 PHY data rates showed that smaller data rates can have higher loss rates in many situations. This can be explained by the fact that packets at lower datarates take longer time on air and are thus more likely to collide with external traffic. Other studies by Raman *et al.* [7] show that weather conditions don’t have noticeable effects on loss rates in long distance links.

2.5 Impact on TCP

Taken together, the protocol shortcomings of 802.11 and channel induced losses significantly lower end-to-end TCP performance. The use of stop-and-wait over long

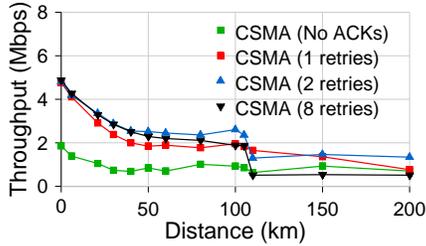


Figure 5: Cumulative throughput for TCP in both directions simultaneously over standard CSMA with 10% channel loss on emulated link. Traffic is 802.11b at PHY layer datarate of 11Mbps.

distances reduces channel utilization. In addition, we see correlated bursty collision losses due to interference from unsynchronized transmissions (over both single-link and multi-hop scenarios) as well as from external WiFi sources. Under these conditions, TCP flows often timeout resulting in very poor performance. The only configurable parameter in the driver is the number of packet retries. Setting a higher value on the number of retries decreases the loss rate, but at the cost of lower throughput resulting from lower channel utilization.

To better understand this trade-off, we measure the aggregate throughput of TCP flows in both directions on an emulated link while varying distance and introducing a channel packet loss rate of 10%. Figure 5 presents the aggregate TCP throughput with various number of MAC retries of the standard 802.11 MAC. Due to increased collisions and larger ACK turnaround times, throughput degrades gradually with increasing distances.

3 WiLDNet Design

In this section, we describe the design of WiLDNet and elaborate on how it addresses the 802.11 protocol shortcomings as well as achieves good performance in high-loss environments. In the previous section, we identified three basic problems with 802.11; (a) low utilization, (b) collisions at long distances, and (c) inter-link interference. To address the problem of low utilization, we propose the use of bulk packet acknowledgments (Section 3.1). To mitigate loss from collisions at long distances as well as inter-link interference, we replace the standard CSMA MAC with a TDMA-based MAC protocol. We build upon 2P [17] to adapt it to high-loss environments (Section 3.2). Additionally, to handle the challenge of high and variable packet losses, we design adaptive loss recovery mechanisms that use a combination of FEC and retransmissions with bulk acknowledgments (Section 3.3).

WiLDNet follows three main design principles. First, the system should not be narrowly focused to a single set of application types. It should be configurable to provide a broad tradeoff spectrum across different end-to-

end properties including delay, bandwidth, loss, reliability and jitter. Second, all mechanisms proposed should be implementable on commodity off-the-shelf 802.11 cards. Third, the design should be lightweight, such that it can be implemented on the resource-constrained single-board computers (266-MHz CPU and 128 MB memory) used in our testbed.

3.1 Bulk Acknowledgments

We begin with the simple case of a single WiLD link, with each node having a half-duplex radio. As shown earlier, when propagation delays become longer, the default CSMA mechanism cannot determine whether the remote peer is sending a packet in time to back-off its own transmission and avoid collisions. Moreover, such a contention-based mechanism is overkill when precisely two hosts share the channel for a directional link.

Thus, a simple and efficient solution to avoid these collisions is to use an echo protocol between the sender and the receiver, which allows the two end-points to take turns sending and receiving packets. Hence, from a node’s perspective, we divide time into send and receive time slots, with a burst of several packets being sent from one host to its peer in each slot.

Consequently, to improve link utilization, we replace the stock 802.11 stop-and-wait protocol with a sliding-window based flow-control approach in which we transmit a *bulk acknowledgment* (bulk ACK) from the receiver for a window of packets. We generate a bulk ACK as an aggregated acknowledgment for all the packets received within the previous slot. In this way, a sender can rapidly transmit a burst of packets rather than wait for an ACK after each packet.

The bulk ACK can be either piggybacked on data packets sent in the reverse direction, or sent as one or more stand-alone packets if no data packets are ready. Each bulk ACK contains the sequence number of the last packet received in order and a variable-length bit vector ACK for all packets following the in-order sequence. Here, the sequence number of a packet is locally defined between the pair of end-points of a WiLD link.

Like 802.11, the bulk ACK mechanism is not designed to guarantee perfect reliability. 802.11 has a maximum number of retries for every packet. Similarly, upon receiving a bulk ACK, the sender can choose to advance the sliding window skipping unacknowledged packets if the retry limit is exceeded. In practice, we support different retry limits for packets of different flows. The bulk ACK mechanism introduces packet reordering at the link layer, which may not be acceptable for TCP traffic. To handle this, we provide in-order packet delivery at the link layer either for the entire link or at a per-flow basis.

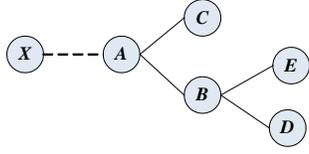


Figure 6: Example topology to compare synchronization of 2P and WiLDNet.

3.2 Designing TDMA on Lossy Channels

To address the inappropriateness of CSMA for WiLD networks, 2P [17] proposes a contention-free TDMA based channel access mechanism. 2P eliminates inter-link interference by synchronizing all the packet transmissions at a given node (along all links which operate on the same channel). In 2P, a node in transmission mode simultaneously transmits on all its links for a globally known specific period, and then explicitly notifies the end of its transmission period to each of its neighbors using marker packets. A receiving node waits for the marker packets from all its neighbors before switching over to transmission mode. In the event of a loss of a marker packet, a receiving node uses a timeout to switch into the transmission mode.

The design of 2P, while functional, is not well suited for lossy environments. Consider the simple example illustrated in Figure 6, where all links operate on the same channel. Consider the case where (X, A) is the link experiencing high packet loss-rate. Let T denote the value of the time-slot. Whenever a marker packet transmitted by X is lost, A begins transmission only after a timeout period $T_0 (\geq T)$. This, in turn, delays the next set of transmissions from nodes B and C to their other neighbors by a time period that equals $T_0 - T$. Unfortunately, this propagation of delay does not end here. In the time slot that follows, D 's transmission to its neighbors is delayed by $T_0 - T$. Hence, what we observe is that the loss of marker packets has a “ripple effect” in the entire network creating an idle period of $T_0 - T$ along every link. When markers along different links are dropped, the ripples from multiple links can interact with each other and cause more complex behavior.

Ideally, one would want $T_0 - T$ to be very small. If all nodes are perfectly time synchronized, we can set $T_0 = T$. However, in the absence of global time synchronization, one needs to set a conservative value for T_0 . 2P chooses $T_0 = 1.25 \times T$. The loss of a marker packet leads to an idle period of $0.25 \times T$ (in 2P, this is 5 ms for $T = 20$ ms). In bursty losses, transmitting multiple marker packets may not suffice.

Given that many of the links in our network experience sustained loss-rates over 5–40%, in WiLDNet, we use an implicit synchronization approach that aims to reduce the value of $T_0 - T$. In WiLDNet, we use a simple loose time synchronization mechanism similar to the basic linear time synchronization protocol NTP [13], where

during each time slot along each link, the sender acts as the master and the receiver as the slave. Consider a link (A, B) where A is the sender and B is the receiver at a given time. Let t_{send_A} and t_{recv_B} denote the start times of the slot as maintained by A and B . All the packets sent by A are timestamped with the time difference (δ) between the time the packet has been sent (t_1) and the beginning of the send slot (t_{send_A}). When a packet is received by B at time t_2 , the beginning of B 's receiving slot is adjusted accordingly: $t_{recv_B} = t_2 - \delta$. As soon as B 's receive slot is over, and $t_{send_B} = t_{recv_B} + T$ is reached, B starts sending for a period T .

Due to the propagation delay between A and B , the send and corresponding receive slots are slightly skewed. The end-effect of this loose synchronization is that the value of $T_0 - T$ is limited by the propagation delay across the link even with packet losses (assuming clock speeds are roughly comparable). Hence, an implicit synchronization approach significantly reduces the value of $T_0 - T$ thereby reducing the overall number of idle periods in the network.

3.3 Adaptive Loss Recovery

To achieve predictable end-to-end performance, it is essential to have a loss recovery mechanism that can hide the loss variability in the underlying channel. Achieving such an upper bound (q) on the loss-rate perceived by higher level applications is not easy in our settings. First, it is hard to predict the arrival and duration of bursts. Second, the loss distribution that we observed on our links is non-stationary even on long time scales (hourly and daily basis). Hence, a simple model cannot capture the channel loss characteristics.

In WiLDNet, we can either use retransmissions or FEC to deal with losses (or a combination of both). A retransmission based approach can achieve the loss-bound q with minimal throughput overhead but at the expense of increased delay. An FEC based approach incurs additional throughput overhead but does not incur a delay penalty especially since it is used in combination with TDMA on a per-slot basis. However, an FEC approach cannot achieve arbitrarily low loss-bounds mainly due to the unpredictability of the channel.

3.3.1 Tuning the Number of Retransmissions

To achieve a loss bound q independent of underlying channel loss rate $p(t)$, we need to tune the number of retransmissions. One can adjust the number of retransmissions $n(t)$ for a channel loss-rate $p(t)$ such that $(1 - p(t))^{n(t)} = q$. Given that our WiLD links support in-order delivery (on a per-flow or on whole link basis), a larger $n(t)$ also means a larger maximum delay, equal to $n(t) * T$ for a slot period T . One can set different values of $n(t)$ for different flows. We found that estimating $p(t)$ using an exponentially weighted average is sufficient in

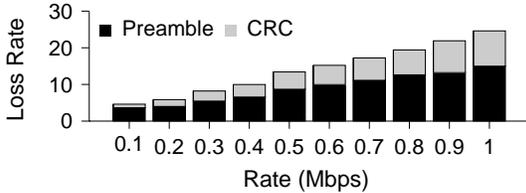


Figure 7: Proportion of CRC and preamble errors in channel loss. Traffic is at UDP CBR packets of 1440 bytes each at 802.11b PHY datarate of 11Mbps. Main link is sending at 2Mbps. The sending rate of the interferer increases from 0.1Mbps to 1Mbps.

our links to achieve the target loss estimate q . A purely retransmission based recovery mechanism has minimal throughput overhead as only the lost packets are retransmitted but this comes at a cost of high delay due to the long round-trip times over WiLD links.

3.3.2 Adaptive FEC-Based Recovery

Designing a good FEC mechanism in highly variable lossy conditions requires accurate estimation of the underlying channel loss. When the loss is underestimated, the redundant packets cannot be decoded at all making them useless, but overestimating the loss rate leads to unnecessary overhead.

Motivating inter-packet FEC: We can perform two types of FEC: inter-packet FEC (coding across packets) or intra-packet FEC (coding redundant blocks within a packet). Based on extensive measurements on a wireless channel emulator we observe that in presence of external WiFi interference, lost packets can be categorized into either CRC errors or preamble errors. A CRC error packet is received by the driver with a check sum error. However, an error in the preamble leads to the entire packet being dropped completely. Figure 7 shows the breakup of the loss rate with increasing external interference. We observe although the proportion of preamble errors decreases as external interference increases, it still causes at least 50% of all errors. Moreover a substantial number of the CRC error packets were truncated. We choose not to perform intra-packet FEC because it can only help recover packets that have CRC errors. Hence, we chose to perform inter-packet FEC.

Estimating redundancy: We apply FEC in combination with TDMA. For every time slot of N packets, we add $N - K$ redundant packets to K original packets. To estimate the redundancy factor, $r = (N - K)/K$, we choose a simple but not perfect estimation policy based on a weighted average of the losses observed in the previous M time slots. Here, we specifically chose a small value of $M = 10$ because it is hard to predict the start of a burst. Secondly, a small value of M , can quickly adapt to both the start and end of a loss burst saving unnecessary redundant FEC packets. For a time slot of $T = 10ms$, $M = 10$ corresponds to $200ms$ (with symmetric slot al-

location in both directions) to adapt to a change in the loss behavior. Also due to non-stationary loss distributions, the benefit of using more complicated distribution based estimation approaches [22] is marginal. This type of FEC is best suited for handling residual losses and bursts that are longer than the time required for loss estimation mechanism to adapt.

4 Implementation

In this section, we describe the implementation details of WiLDNet. Our implementation comprises two parts: (a) driver-level modifications to control or disable features implemented in hardware (Section 4.1); (b) a *shim* layer that sits above the 802.11 MAC (Section 4.2) and uses the Click [11] modular router software to implement the functionalities described in Section 3.

4.1 Driver Modifications

The wireless cards we use in our implementation are the high power (200-400 mW) Atheros-based chipsets. To implement WiLDNet, we have to disable the following 802.11 MAC mechanisms:

- We disable **link-layer association** in Atheros chipsets using the *AdHoc-demo* mode.
- We disable **link layer retransmissions and automatic ACKs** by using 802.11 QoS frames with WMM extensions set to the no-ACK policy.
- We disable **CSMA** by turning off the Clear Channel Assessment (CCA) in Atheros chipsets. With CCA turned off, the radio card can transmit packets right away without waiting for a clear channel.

4.2 Software Architecture Modifications

In order to implement single-link and inter-link synchronization using TDMA, the various loss recovery mechanisms, sliding window flow control, and packet reordering for in-order delivery, we use the Click modular router [11] framework. We use Click because it enables us to prototype quickly a modular MAC layer by composing different Click elements together. It is also reasonably efficient for packet processing especially if loaded as a kernel module. Using kernel taps, Click creates fake network interfaces, such as *fake0* in Figure 8 and the kernel communicates with these virtual interfaces. Click allows us to intercept packets sent to this virtual interface and modify them before sending them on the real wireless interface and vice versa.

Figure 8 presents the structure of the Click elements of our layered system, with different functionality (and corresponding packet header processing) at various layers:

Incoming/Outgoing Queues: The mechanisms for sliding window packet flow, bulk ACKs, selective retransmission and reordering for in-order delivery are implemented by the incoming/outgoing queue pair. Packet buffering at the sender is necessary for retransmissions,

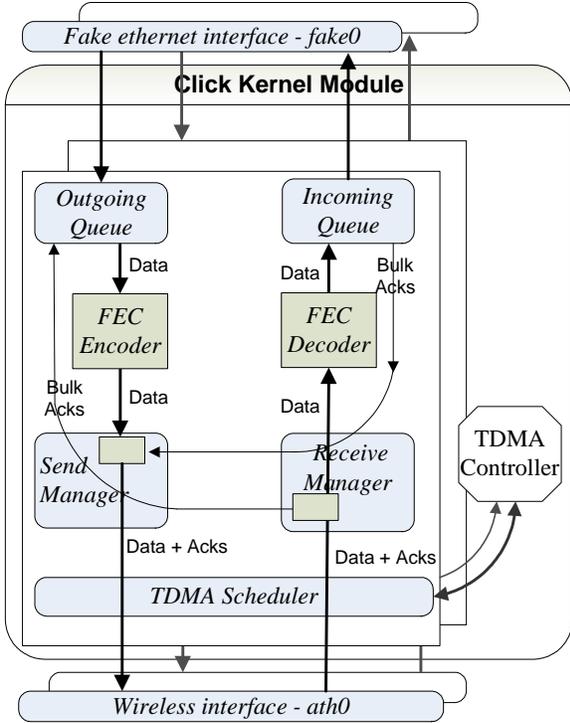


Figure 8: Click Module Data Flow

and buffering at the receiver enables reordering. In-order delivery and packet retransmission are optional, and the number of retries can be set on a per-packet basis.

FEC Encoder/Decoder: An optional layer is responsible for inter-packet forward error correction encoding and decoding. For our implementation we modify a FEC library [19] that uses erasure codes based on Vandermonde matrices computed over $GF(2^m)$. This FEC method uses a (K, N) scheme, where the first K packets are sent in their original form, and $N - K$ redundant packets are generated, for a total of N packets sent. At the receiver, the reception of any K out of the N packets enables the recovery of the original packets. We choose this scheme because, in loss-less situations, it introduces very low latency: the original K packets can be immediately sent by the encoder (without undergoing encoding), and immediately delivered to the application by the decoder (without undergoing decoding).

TDMA Scheduler and Controller: The Scheduler ensures that packets are being sent only during the designated send slots, and manages packet timestamps as part of the synchronization mechanism. The Controller implements synchronization among the wireless radios, by enforcing synchronous transmit and receive operation (all the radios on the same channel have a common send slot, followed by a common receive slot).

4.2.1 Timing issues

We do not use Click timers to implement time synchronization because the underlying kernel timers are not

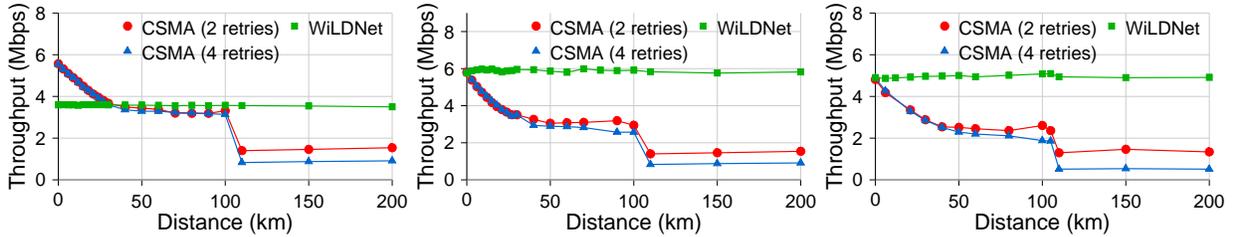
precise at the granularity of our time slots (10ms-40ms) on our hardware platform (266MHz CPU). Also packet queuing in the wireless interface causes variability in the time between the moment Click emits a packet and the time the packet is actually sent on the air interface. Thus, the propagation delay between the sending and the receiving click modules on the two hosts is not constant, affecting time slot calculations. Fortunately, this propagation delay is predictable for the first packet in the send slot, when the hardware interface queues are empty. Thus, in our current implementation, we only timestamp the first packet in a slot, and use it for adjusting the receive slot at the peer. If this packet is lost, the receiver's slot is not adjusted in the current slot, but since the drift is slow this does not have a significant impact. In the future we intend to perform this timestamping in the firmware - that would allow us to accurately timestamp every packet just before packet transmission.

Another timing complication is related to estimating whether we have time to send a new packet in the current send slot. Since the packets are queued in the wireless interface, the time when the packet leaves Click cannot be used to estimate this. To overcome this aspect, we use the notion of *virtual time*. At the beginning of a send slot, the virtual time t_v is same as current (system) time t_c . Every time we send a packet, we estimate the transmission time of the packet on the channel and recompute the virtual time: $t_v = \max(t_c, t_v) + \text{duration}(\text{packet})$. A packet is sent only after checking that the virtual time after sending this packet will not exceed the end of the send slot. Otherwise, we postpone the packet until the next slot.

5 Experimental Evaluation

The main goals of WiLDNet are to increase link utilization and to eliminate the various sources of packet loss observed in a typical multi-hop WiLD deployment, while simultaneously providing flexibility to meet different end-to-end application requirements. We believe these are the first actual implementation results over an outdoor multi-hop WiLD network deployment.

Raman *et al.* [17] show the improvements gained by the 2P-MAC protocol in simulation and in an indoor environment. However, a multi-hop outdoor deployment also has to deal with high losses from external interference. 2P in its current form does not have any built-in recovery mechanism and it is not clear how any recovery mechanism can be combined with the marker-based synchronization protocol. Hence, we do not have any direct comparison results with 2P on our outdoor wireless links. Also, the proof-of-concept implementation of 2P was for the Prism 2.5 wireless chipset and it would be non-trivial to implement the same in WiLDNet using features of the Atheros chipset.



(a) TCP flow in one direction (b) TCP flow in both directions (c) TCP in both directions, 10% channel loss

Figure 9: TCP throughput for WiLDNet vs 802.11 CSMA. Each measurement is for a TCP flow of 60s, 802.11b PHY, 11Mbps.

Our evaluation has three main parts:

- We analyze the ability of WiLDNet to maintain high performance (high link utilization) over long-distance WiLD links. At long distances, we demonstrate 2–5x improvements in cumulative throughput for TCP flows in both directions simultaneously.
- Next, we evaluate the ability of WiLDNet to scale to multiple hops and eliminate inter-link interference. WiLDNet yields a 2.5x improvement in TCP throughput on our real-world multi-hop setup.
- Finally, we evaluate the effectiveness of the two link recovery mechanisms of WiLDNet: Bulk Acks and FEC.

5.1 Single Link

In this section we demonstrate the ability of WiLDNet to eliminate link under-utilization and packet collisions over a single WiLD link. We compare the performance of WiLDNet (slot size of 20ms) with the standard 802.11 CSMA (2 retries) base case.

The first set of results show the improvement of WiLDNet on a single emulator link with increasing distance. Figure 9(a) compares the performance of TCP flowing only in one direction. The lower throughput of WiLDNet, approximately 50% of channel capacity, is due to symmetric slot allocation between the two end points of the link. However, over longer links (>50 km), the TDMA-based channel allocation avoids the under-utilization of the link as experienced by CSMA. Also, beyond 110 km (the maximum possible ACK timeout), the throughput with CSMA drops rapidly because of unnecessary retransmits (Section 2.3.1). Figure 9(b) shows the cumulative throughput of TCP flowing simultaneously in both directions. In this case, WiLDNet effectively eliminates all collisions occurring in presence of bidirectional traffic. TCP throughput of 6 Mbps is maintained for all distances.

Table 1 compares WiLDNet and CSMA for some of our outdoor wireless links. We show TCP throughput in one direction and the cumulative throughput for TCP simultaneously flowing in both directions. Since these are outdoor measurements, there is significant variation over time and we show both the mean and standard deviation for the measurements. We can see that as the link dis-

Link	Distance (km)	Loss rates (%)	802.11 CSMA (Mbps)		WiLDNet (Mbps)	
			One dir	Both dir	One dir	Both dir
B-R	8	3.4	5.03 (0.02)	4.95 (0.03)	3.65 (0.01)	5.86 (0.05)
P-S	45	2.6	3.62 (0.20)	3.52 (0.17)	3.10 (0.05)	4.91 (0.05)
Ghana	65	1.0	2.80 (0.20)	0.68 (0.39)	2.98 (0.19)	5.51 (0.07)

Table 1: Mean TCP throughput (flow in one direction and cumulative for both directions simultaneously) for WiLDNet and CSMA for various outdoor links (distance and loss rates). The standard deviation is shown in parenthesis for 10 measurements. Each measurement is for TCP flow of 30s at a 802.11b PHY-layer datarate of 11Mbps.

tance increases, the improvement of WiLDNet is more substantial. Infact, for the 65 km link in Ghana, WiLDNet’s throughput at 5.5 Mbps is about 8x better than standard CSMA.

5.2 Multiple Hops

This section validates that WiLDNet eliminates inter-link interference by synchronizing receive and transmit slots in TDMA resulting in up to 2x TCP throughput improvements over standard 802.11 CSMA in multi-hop settings.

The first set of measurements were performed on our indoor setup (Section 2.2) where we recreated the conditions of a linear outdoor multi-hop topology using the RF isolation boxes. Thus transmissions from local radios interfere with each other but multiple local radio interfaces can receive simultaneously. We then measure TCP throughput of flows in the one direction and then both directions simultaneously for both standard 802.11 CSMA and WiLDNet (with slot size of 20ms). All the links were operating on the same channel. As we see in Table 2, as the number of hops increases, standard 802.11’s TCP throughput drops substantially when transmissions from a radio collide with packet reception on a nearby local radio on the same node. WiLDNet avoids these collisions and maintains a much higher cumulative TCP throughput (up to 2x for the 3-hop setup) by proper synchronization of send and receive slots.

Linear setup	802.11 CSMA (Mbps)			WiLDNet (Mbps)		
	Dir 1	Dir 2	Both	Dir 1	Dir 2	Both
2 nodes	5.74 (0.01)	5.74 (0.01)	6.00 (0.01)	3.56 (0.03)	3.53 (0.02)	5.85 (0.07)
3 nodes	2.60 (0.01)	2.48 (0.01)	2.62 (0.01)	3.12 (0.01)	3.12 (0.01)	5.12 (0.03)
4 nodes	2.23 (0.01)	2.10 (0.01)	1.99 (0.02)	2.95 (0.05)	2.98 (0.04)	4.64 (0.24)

Table 2: Mean TCP throughput (flow in each direction and cumulative for both directions simultaneously) for WiLDNet and standard 802.11 CSMA. Measurements are for linear 2,3 and 4 node indoor setups recreating outdoor links running on the same channel. The standard deviation is shown in parenthesis for 10 measurements of flow of 60s each at 802.11b PHY layer datarate of 11Mbps.

Description (Mbps)	One direction	Both directions
Standard TCP: same channel	2.17	2.11
Standard TCP: diff channels	3.95	4.50
WiLD TCP: same channel	3.12	4.86
WiLD TCP: diff channels	3.14	4.90

Table 3: Mean TCP throughput (flow in single direction and cumulative for both directions simultaneously) comparison for WiLDNet and standard 802.11 CSMA over a 3-hop outdoor setup ($K \leftrightarrow P \leftrightarrow M$). Averaged over 10 measurements of TCP flow for 60s at 802.11b PHY layer datarate of 11Mbps.

We can also see that although WiLDNet has more than 2x improvement over standard 802.11, the final throughput (4.6Mbps) is still much smaller than the raw throughput of the link (6-7Mbps). This can be attributed to the overhead of synchronization and packet processing in Click running on our low-power (266MHz) single board routers. A more efficient synchronization mechanism implemented in the firmware (rather than Click) would deliver much better improvement.

We also measure this improvement on our outdoor testbed between the nodes K and M relayed through node P . We again compare the TCP throughput for WiLDNet and standard 802.11 CSMA with links operating on the same channel. In order to quantify the effect of inter-link interference, we also perform the same experiments with the links operating on different, non-overlapping channels, in which case the inter-link interference is almost zero, as previously shown in Figure 3.

We can see that, for same channel operation, the cumulative TCP throughput in both directions with WiLDNet (4.86 Mbps) is more than twice the throughput observed over standard 802.11 (2.11 Mbps). The improvement is substantially lower for the unidirectional case (3.14 Mbps versus 2.17 Mbps), because the WiLD links are constrained to send in one direction only roughly half of the time.

Another key observation is that WiLDNet is capable of eliminating almost all inter-link interference. This is

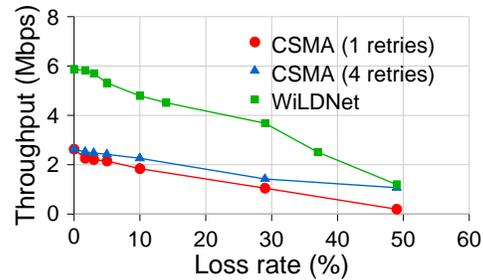


Figure 10: Comparison of cumulative throughput for TCP in both directions simultaneously for WiLDNet and standard 802.11 CSMA with increasing loss on 80km emulated link. Each measurement was for 60s TCP flows of 802.11b at 11Mbps PHY datarate.

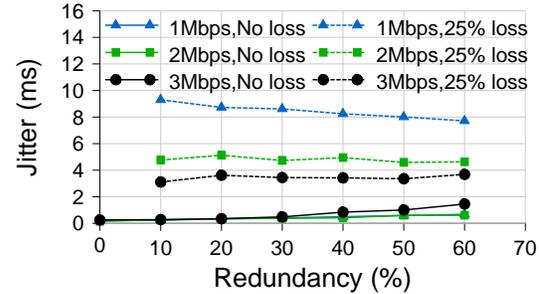


Figure 11: Jitter overhead of encoding and decoding for WiLDNet on single indoor link. Traffic is 1440 byte UDP CBR packets at PHY datarate of 11Mbps in 802.11b.

shown by the fact that the throughput achieved by WiLDNet is almost the same, whether the links operate on the same channel or on non-overlapping channels.

5.3 WiLDNet Link-Recovery Mechanisms

Our next set of experiments evaluate WiLDNet's adaptive link recovery mechanisms in conditions closer to the real world, where errors are generated by a combination of collisions and external interference. We evaluate both the bulk ACK and FEC recovery mechanisms.

5.3.1 Bulk ACK Recovery Mechanism

For our first experiment, presented in Figure 9(c), we vary the link length on the emulator, and we introduce a 10% error rate through external interference. We again measure the cumulative throughput of TCP flows in both directions for WiLDNet and standard 802.11 CSMA. As can be seen, WiLDNet maintains a constant throughput with increasing distance as opposed to the 802.11 CSMA. Due to the 10% error, WiLD incurs a constant throughput penalty of approximately 1 Mbps compared to the no-loss case in Figure 9(b).

In our second experiment we fix the distance in the emulator setup to 80 km, and vary channel loss rates. The results in Figure 10 show that WiLDNet maintains roughly a 2x improvement over standard CSMA's recovery mechanism for packet loss rates up to 30%.

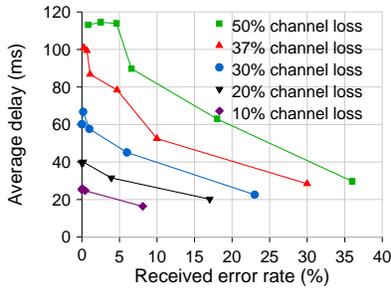


Figure 12: Avg. delay with decreasing target loss rate (X-axis) for various loss rates in WiLDNet on single emulated 60km link (slot size=20ms).

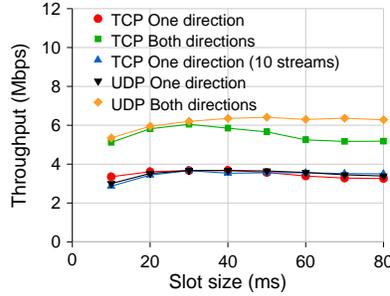


Figure 13: Throughput for increasing slot sizes (X-axis) in WiLDNet for various types of traffic on single emulated 60km link.

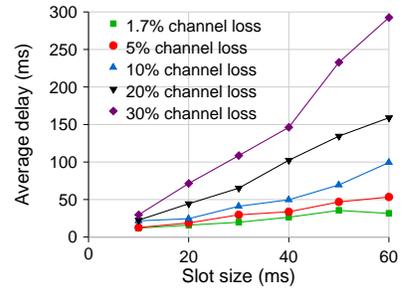


Figure 14: Avg. delay at increasing slot sizes (X-axis) for various loss rates in WiLDNet on single emulated 60km link.

5.3.2 Forward Error Correction (FEC)

To measure the jitter introduced by the FEC mechanism, we performed a simple experiment where we measured the jitter of a flow under two conditions: in the absence of any loss and in the presence of a 25% loss. Figure 11 illustrates the jitter introduced by WiLDNet’s FEC implementation. We can see that in the absence of any loss, when only encoding occurs, the jitter is minimal. However, in the presence of loss, when decoding also takes place, the measured jitter increases. However, the magnitude of the jitter is very small and well within the acceptable limits of many interactive applications (voice or video), and decreases with higher throughputs (since the decoder waits less for redundant packets to arrive).

Moreover, considering the combination of FEC with TDMA, the delay overheads introduced by these methods overlap, since the slots when the host is not actively sending can be used to perform encoding without incurring any additional delay penalties.

6 Tradeoffs

One of the main design principles of WiLDNet is to build a system that can be configured to adapt to different application requirements. In this section we explore the tradeoff space of throughput, delay and delivered error rates by varying the slot size, number of bulk retransmissions and FEC redundancy parameters. We observe that WiLDNet can perform in a wide spectrum of the parameter space, and can easily be configured to meet specific application requirements.

6.1 Choosing number of retransmissions

The first tradeoff that we explore is choosing the number of retries to get a desired level of final error rate on a WiLD link. Although retransmission based loss recovery achieves optimal throughput utilization, it comes at a cost of increased delay; the loss rate can be reduced to zero by arbitrarily increasing the number of retransmissions at the cost of increased delay. This tradeoff is illustrated in Figure 12 which shows a plot of delay versus error

rate for varying channel loss rates (10% to 50%). Retries are decreased from 10 to 0 from left to right for a given series in the figure. All the tests are with unidirectional UDP at 1 Mbps for a fixed slot size of 20ms on a single emulator 60km link. We can see that as we try to reduce the final error rate at the receiver, we have to use more retries and this increases the average delay. In addition, we also observe that larger the number of retries, larger the end-to-end jitter (especially at higher loss rates).

This tradeoff has important implications for applications that are more sensitive to delay and jitter (such as real time audio and video) as compared to applications which require high reliability. For such applications, we can achieve a balance between the final error rate and the average delay by choosing an appropriate retry limit. For applications that require improved loss characteristics without incurring a delay penalty, we need to use FEC for loss recovery.

6.2 Choosing slot size

The second tradeoff that we explore is the effect of slot size on TCP and UDP throughput. Our experiments are performed on a 60-km emulated link (Figure 13). As discussed in Section 3.2, switching between send and receive slots incurs a non-negligible overhead for the Click based WiLDNet implementation. This overhead although constant for all slot sizes, occupies a higher fraction of the slot for smaller slot sizes. As a consequence, at small slot sizes the achieved throughput is lower. However, the UDP throughput levels off beyond a slot size of 20 ms. We also observe the TCP throughput reducing slightly at higher slot size. This is because the bandwidth-delay product of the link increases with slot size, but the send TCP window sizes are fixed. UDP throughput does not decrease at higher slot sizes.

In the next experiment, we measure the average UDP packet transmission delay while varying the slot size, for several channel error rates. The results are presented in Figure 14; each series represents a unidirectional UDP test (1 Mbps CBR) at a particular channel loss rate with

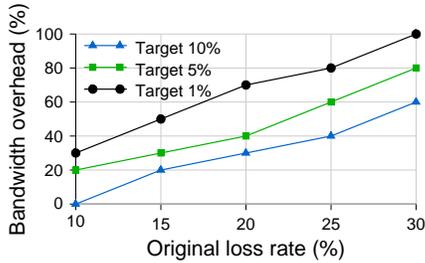


Figure 15: Throughput overhead vs channel loss rate for FEC on single emulated 20km link. Traffic is 1Mbps CBR UDP.

WiLDNet using maximum number of retries. Figure 14 shows the increase in delay with increasing slot size. It is clear that slot sizes beyond 20 ms do not result in substantially higher throughputs, but they do result in much larger delay. However, if lower delay is required, smaller slots can be used at the expense of some throughput overhead consumed by the switching between the transmit and receive modes.

6.3 Choosing FEC parameters

The primary tunable FEC parameter is the redundancy factor $r = (N - K)/K$, also referred to as throughput overhead. Although FEC incurs a higher throughput overhead than retransmissions, it incurs a smaller delay penalty as illustrated earlier in Section 5.3.2. To analyze the tradeoff between FEC throughput overhead and the target loss-rate, we consider the case of a single WiLD link (in our emulator environment) with a simple Bernoulli loss-model (every packet is dropped with probability p). Figure 15 shows the amount of redundancy required to meet three different target loss-rates of 10%, 5% or 1% as the raw channel error rates (namely p) increase. We see that in order to achieve very low target loss-rates, a lot of redundancy is required (for example, FEC incurs a 100% overhead to reduce the loss-rate from 30% to 1%). Also, when a channel is very bursty and has an unpredictable burst arrival pattern, it is very hard for FEC to achieve arbitrarily low target loss-rates.

For applications that can tolerate one round of retransmissions, we can use a combination of FEC and retransmissions to provide a tradeoff between overall throughput overhead, delay and target loss-rate. In the case of a channel with a stationary loss distribution, OverQoS [22] shows that the optimal policy to minimize overhead is to not use FEC in the first round but use it in the second round to pad retransmission packets. With unpredictable and highly varying channel loss conditions, an alternative promising strategy is to use FEC in the first round during bursty periods to reduce the perceived loss-rate.

7 Related Work

Long Distance WiFi: The use of 802.11 for long distance networking with directional links and multiple radios per node, raises a new set of technical issues that

were first illustrated in [4]. Raman *et al.* built upon this work in [17, 16] and proposed the 2P MAC protocol. WiLDNet builds upon 2P to make it robust in high loss environments. Specifically we modify 2P’s implicit synchronization mechanism as well as build in adaptive bulk ACK based and FEC based link recovery mechanisms.

Other wireless loss recovery mechanisms: There is a large body of research literature in wireless and wire-line networks that have studied the tradeoffs between different forms of loss recovery mechanisms. Many of the classic error control mechanisms are summarized in the book by Lin and Costello [12]. OverQoS [22] performs recovery by analyzing the FEC/ARQ tradeoff in variable channel conditions and the Vandermonde codes are used for reliable multicast in wireless environments [19].

Of particular interest for this work are the Berkeley Snoop protocol [2] which provides transport-aware link-layer recovery mechanisms in wireless environments. To compare the WiLDNet bulk ACK recovery mechanism with recovery at a higher layer, we experimented with a version of the original Snoop protocol [3] that we modified to run on WiLD links. Basically, each WiLD router ran one half of Snoop, the fixed host to mobile host part, for each each outgoing link and integrated all the Snoops on different links into one module.

We measured the performance of modified Snoop as a recovery mechanism over both standard 802.11 (CSMA) and over WiLDNet with no retries. We found that WiLDNet was still 2x better than Snoop. We also saw that Snoop was better than vanilla CSMA only at lower error rates (less than 10%). Thus, this indicates that higher layer recovery mechanisms might be better than stock 802.11 protocol, but only at lower error rates.

Other WiFi-based MAC protocols: Several recent efforts have focused on leveraging off-the-shelf 802.11 hardware to design new MAC protocols. Overlay MAC Layer (OML) [18] provides a deployable approach towards implementing a TDMA style MAC on top of the 802.11 MAC using loosely-synchronized clocks to provide applications and competing nodes better control over the allocation of time-slots. SoftMAC [14] is another platform to build experimental MAC protocols. MultiMAC [10] builds on SoftMac to provide a platform where multiple MAC layers co-exist in the network stack and any one can be chosen on a per-packet basis.

WiMax: An alternative to WiLD networks is WiMax [25]. WiMax does present many strengths over a WiFi: configurable channel spectrum width, better modulation (especially for non-line of sight scenarios), operation in licensed spectrum with higher transmit power, and thus longer distances. On the other hand, WiMax currently is primarily intended for carriers (like cellular) and does not support point-to-point operation. In addition, WiMax base-stations are expen-

sive (\$10,000) and the high spectrum license costs in most countries dissuades grassroots style deployments. Currently it is also very difficult to obtain licenses for experimental deployment and we are not aware of open-source drivers for WiMax base-stations and clients. However, most of our work in loss recovery and adaptive FEC would be equally valid for any PHY layer (WiFi or WiMax). With appropriate modifications and cost reductions, WiMax can serve as a more suitable PHY layer for WiLD networks.

8 Future Work and Conclusion

The commoditization of WiFi (802.11 MAC) hardware has made WiLD networks an extremely cost-effective option for providing network connectivity, especially in rural regions in developing countries. However providing coverage at high performance in real-world WiLD network deployments raises many research challenges: optimal planning and placement of long distance links, design of appropriate MAC and network protocols to provide quality of service to a wide variety of applications, remote management and fault tolerance to handle unpredictable node and link failures [23].

One of the most important challenges in this space is the sub-optimal performance of the standard 802.11 MAC protocol. In this paper, we identify the set of link- and MAC-layer modifications essential for achieving high throughput in multi-hop WiLD networks. Specifically, using a detailed performance evaluation, we show that the conventional 802.11 protocol is ill-suited for WiLD settings. Our proposed solution provides a 2-5x improvement in TCP throughput over the conventional 802.11 MAC.

Although this constitutes a substantial improvement, designing decentralized TDMA slot scheduling schemes for multi-hop and multi-channel networks to achieve optimal bandwidth and delay characteristics for realistic real-world asymmetric traffic demands is a significant future research direction. Our current solution builds the basic link mechanisms to provide quality of service. We intend to build end-to-end QoS solutions that leverage these mechanisms and adapt to a realistic traffic mix.

Encouraged by our initial results on our long distance outdoor testbed, we will now implement these modifications in our live rural deployments in India and Ghana. We expect that these improvements can have significant impact in accelerating the penetration of feasible network connectivity options in developing regions.

Acknowledgments

We thank the whole TIER group at UC Berkeley and Intel Research, Berkeley for braving wind, sun, rain and crazy taxi drivers to set up long-distance links in India, Ghana and the Bay Area so that we can run our experiments. We thank all the anonymous reviewers for their

feedback and owe our gratitude to Brad Karp, our NSDI shepherd for his valuable comments which helped in substantially improving the paper.

References

- [1] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris. Link-level Measurements from an 802.11b Mesh Network. In *ACM SIGCOMM*, Aug. 2004.
- [2] H. Balakrishnan. *Challenges to Reliable Data Transport over Heterogeneous Wireless Networks*. PhD thesis, University of California at Berkeley, Aug. 1998.
- [3] H. Balakrishnan, S. Seshan, E. Amir, and R. Katz. Improving TCP/IP Performance over Wireless Networks. In *ACM MOBICOM*, Nov. 1995.
- [4] P. Bhagwat, B. Raman, and D. Sanghi. Turning 802.11 Inside-out. *ACM SIGCOMM CCR*, 2004.
- [5] S. Biswas and R. Morris. Opportunistic Routing in Multi-Hop Wireless Networks. *Hotnets-II*, November 2003.
- [6] E. Brewer. Technology Insights for Rural Connectivity. Oct. 2005.
- [7] K. Chebrolu, B. Raman, and S. Sen. Long-Distance 802.11b Links: Performance Measurements and Experience. In *ACM MOBICOM*, 2006.
- [8] Connecting Rural Communities with WiFi. <http://www.crc.net.nz>.
- [9] Digital Gangetic Plains. <http://www.iitk.ac.in/mladgp/>.
- [10] C. Doerr, M. Neufeld, J. Fifield, T. Weingart, D. C. Sicker, and D. Grunwald. MultiMAC - An Adaptive MAC Framework for Dynamic Radio Networking. In *IEEE DySPAN*, Nov. 2005.
- [11] E. Kohler, R. Morris, B. Chen, J. Jannotti, and M. F. Kaashoek. The Click Modular Router. *ACM Transactions on Computer Systems*, 18(3):263–297, Aug. 2000.
- [12] S. Lin and D. Costello. *Error Control Coding: Fundamentals and Applications*. Prentice Hall, 1983.
- [13] D. L. Mills. Internet Time Synchronization: The Network Time Protocol. In *Global States and Time in Distributed Systems*, IEEE Computer Society Press, 1994.
- [14] M. Neufeld, J. Fifield, C. Doerr, A. Sheth, and D. Grunwald. SoftMAC - Flexible Wireless Research Platform. In *HotNets-IV*, Nov. 2005.
- [15] Partnership for Higher Education in Africa. Securing the Linchpin: More Bandwidth at Lower Cost, 2006.
- [16] B. Raman and K. Chebrolu. Revisiting MAC Design for an 802.11-based Mesh Network. In *HotNets-III*, 2004.
- [17] B. Raman and K. Chebrolu. Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks. In *ACM MOBICOM*, Aug. 2005.
- [18] A. Rao and I. Stoica. An Overlay MAC layer for 802.11 Networks. In *MOBISYS*, Seattle, WA, USA, June 2005.
- [19] L. Rizzo. Effective Erasure codes for Reliable Computer Communication Protocols. *ACM CCR*, 1997.
- [20] A. Sheth, S. Nedeveschi, R. Patra, S. Surana, L. Subramanian, and E. Brewer. Packet Loss Characterization in WiFi-based Long Distance Networks. *IEEE INFOCOM*, 2007.
- [21] Spirent Communications. <http://www.spirentcom.com>.
- [22] L. Subramanian, I. Stoica, H. Balakrishnan, and R. Katz. OverQoS: An Overlay Based Architecture for Enhancing Internet QoS. In *USENIX/ACM NSDI*, March 2004.
- [23] L. Subramanian, S. Surana, R. Patra, M. Ho, A. Sheth, and E. Brewer. Rethinking Wireless for the Developing World. *Hotnets-V*, 2006.
- [24] The Akshaya E-Literacy Project. <http://www.akshaya.net>.
- [25] WiMAX forum. <http://www.wimaxforum.org>.