Experimental Study of Transmission Power Control and Blacklisting Based Link Quality Control in Wireless Sensor Networks

ISI-TR-629, January 12, 2007

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We perform systematic experiments to investigate the impact of variable transmission power on link quality. Experimental study presents the causes and significance of link quality variation in real-world deployments. Motivated by our observations from these experiments, we propose a packet-based transmission power control mechanism that incorporates link blacklisting (PCBL) to enhance the performance of data delivery in wireless sensor networks. The effectiveness of the proposed PCBL scheme is demonstrated via comparative testbed experiments considering both single and multiple interfering flows, with and without collision avoidance.

1. INTRODUCTION

The instability and unpredictability of low power wireless channels due to fading and interference make it extremely challenging to provide efficient, reliable routing in wireless sensor networks. However, early research in the context of mobile ad hoc network and wireless sensor networks has often been based on idealized simulation approximations. Although such approximations can be valuable at establishing bounds on performance and exploring algorithms at a high level, they can provide misleading results if not used carefully [Heidemann et al. 2001; Kotz et al. 2004; Min and Chandrakasan 2003]. The most common approximation incorporated in prior wireless multi-hop networking studies has been the distance-based binary link quality estimation (perfect reception within a fixed communication range). Recent empirical studies [Cerpa et al. 2003; Ganesan et al. 2002; Lal et al. 2003; Zhao and Govindan 2003; Kotz et al. 2004] have shown the limitations of such idealized approximations and identified several important characteristics to consider when we develop new protocols and when we analyze the performance of proposed schemes. Unstable and dynamic communication links can often produce results different from our intuition and inconsistent with idealized approximations.

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Findings from single link experiments	**Section 3**
Having unreliable links can be worse than having no links	3.2
Transmission (Tx) power is not an accurate link quality estimator	3.3
RSS is not a good link quality estimator for different receivers	3.4
Link distance is not always a good link quality estimator	3.5
Node location significantly affects link quality due to multi-path	3.6
Link quality variation over time can be reduced with Tx power control	3.7
Tx power needs to be set high enough to reduce link quality variation	3.8
Findings regarding transmission power control with blacklisting	**Section 4**
Blacklisting can satisfy protocol's idealized link quality assumptions	4.4
Power control can significantly improve the throughput of the network	4.5

Table I. Key findings

The central thesis of this work is that efficient control of the link quality is possible by combining transmission power management with link blacklisting strategies. There has been extensive research on transmission power control in wireless networks [ElBatt et al. 2000; Gomez and Campbell 2004; Hou and Li 1986; Kubisch et al. 2003; Li and Sinha 2003; Manousakis and Baras 2003; Monks et al. 2001; Monks et al. 2001; Ramanathan and Rosales-Hain 2000; Rappaport 1996; Rodoplu and Meng 1999; Wattenhofer et al. 2001; Wu et al. 2000; Lin et al. 2006] . However, to our knowledge, most of these studies are based on theoretical analysis or simulations with idealized radio models. In this paper we instead take an experimental approach, thus capturing the full complexities of radio propagation in our testbed. In addition, the primary focuses of prior studies have been on the energy consumption and the network capacity gains from transmission power control; we primarily consider the reliability of the resulting system.

Our contribution in this work is twofold; First, we provide a thorough experimental study of how low-power wireless communication links behave with respect to variable transmission power under different settings. Second, we propose a transmission power control scheme with blacklisting and evaluate its effectiveness in link quality control under multi-hop packet delivery scenarios. This paper extends our prior study of the effects of transmission power control [Son et al. 2004] and updated with new experimental results to understand better of wireless link behaviors (especially with a signal strength metric, sections 3.3 through 3.7) and to demonstrate the performance of the power control mechanism we propose under interference (Section 4.5). We list key findings of this paper in Table I.

Our experiments investigate the possible reasons of link quality variation and identify transmission power ranges where link quality shows high variation (named as *unreliable transmission power range*). Our observations show that the impact of transmission power on quality of a given link is quite sensitive to many factors such as node positions, surrounding environment, and individual hardware differences. We also find that the quality of each link with respect to transmission power can change over time, and the dynamics of the variable power link quality are different for distinct links. We conclude that it is useful to develop a per-link quality control mechanism that chooses a sufficiently high power to reduce link quality variation, while using blacklisting to remove any links that cannot be made high-quality even with power-control from the topology.

Based on our observations, we propose and evaluate a new transmission power control scheme called *power control with blacklisting* or PCBL. The distinguishing characteristic of this scheme is its consideration of empirically determined link quality when adjusting transmission power. It incorporates the following key elements: 1) packet-based power control (considering both packet type and destination) 2) metric-based link quality estimation 3) unreliable link removal (per link or per packet-based blacklisting).

The effectiveness of the transmission power control scheme is evaluated via further testbed experiments that consider both single and multiple flow scenarios (single-hop as well as multi-hop). We also consider the performance both with and without collision avoidance using RTS/CTS messages. In these experiments, we compare the PCBL scheme with constant power schemes without blacklisting as well as maximum power with blacklisting. We find that PCBL shows improved reliability and energy-efficiency under most settings.

2. RELATED WORK

As noted above, there are two strands of research in the literature that are related to our work: (a) some recent experimental studies of wireless links and (b) a larger literature on transmission power control in wireless ad hoc and sensor networks.

2.1 Experimental Studies

Ganesan et al. present a large scale (about 150 nodes) empirical study on a mote-based sensor network; identifying the presence of weak links, link asymmetry etc., and studying their impact on the performance of simple flooding [Ganesan et al. 2002]. Zhao and Govindan perform a detailed study of wireless links with motes under different environments, distances, modulation schemes etc. and identify the existence of a large gray region in distance between connected and disconnected regions where links are highly variant and unreliable [Zhao and Govindan 2003]. The transitional (i.e., gray) region is also observed by Woo et al. who focus on the problem of neighborhood table management and propose mechanisms to blacklist unreliable neighbors in order to provide reliable delivery [Woo et al. 2003]. Zhou et al. study the irregularity of propagated RF signals on different direction. This study provides a useful radio irregularity model (RIM) based on empirical results and analyzes its impact on upper layer protocols together with multiple solutions [Zhou et al. 2004].

Lal et al. study study the impact of link quality metrics such as RSSI and SNR on packet reception rates [Lal et al. 2003]. De Couto et al. introduce the ETX (expected number of transmissions) metric to improve the delivery performance of routing [Couto et al. 2003]. Recently Srinivasan and Levis evaluate and affirm the value of RSSI as a link quality estimator for CC2420 radio [Srinivasan and Levis 2006]. None of these studies [Couto et al. 2003; Ganesan et al. 2002; Lal et al. 2003; Woo et al. 2003; Zhao and Govindan 2003; Zhou et al. 2004; Srinivasan and Levis 2006] primarily focus on link quality control using variable transmission power.

2.2 Transmission Power Control Studies

The literature on topology control, though quite vast, has hitherto focused on slightly different concerns and objectives. Two main research interests of the related work on power control are topology control and channel utilization.

The research on topology control with transmission power [Kawadia and Kumar 2003; Kubisch et al. 2003; Manousakis and Baras 2003; Ramanathan and Rosales-Hain 2000; Rodoplu and Meng 1999; Wattenhofer et al. 2001] are primarily concerned about the energy-efficient network connectivity and the network lifetime issues.

Kubisch et al. [Kubisch et al. 2003] proposed two distributed algorithms which ensures the network connectivity and increases the lifetime of the network. A topology control scheme based on directional information is discussed in [Wattenhofer et al. 2001], where transmission power is increased until at least one neighbor node is found in each direction. Multiple routing daemons are used in CLUSTERPOW [Kawadia and Kumar 2003] protocol to build up separate routing tables at each power level to improve network capacity. Power control mechanisms based on location information are also presented in [Manousakis and Baras 2003; Ramanathan and Rosales-Hain 2000; Rodoplu and Meng 1999] to ensure connectivity while minimizing energy consumption.

Researchers in [ElBatt et al. 2000; Gomez and Campbell 2004; Hou and Li 1986; Li and Sinha 2003; Manousakis and Baras 2003; Monks et al. 2001; Monks et al. 2001; Wu et al. 2000] study the relationship between the level of transmission power and wireless channel utilization. The number of hops in packet delivery and the level of interference in packet transmission are closely related to the transmission power level. ElBatt et al. [ElBatt et al. 2000] proposed a power management protocol to improve throughput in wireless network which has some similarities to the packet-based transmission power control described in our work; however we use more sophisticated link quality statistics and link blacklisting, and make a distinction between unicast and broadcast packets. MAC protocols with a transmission power control functionality are explained in [Monks et al. 2000; 2001; Wu et al. 2000]. Minimum transmission power selection with RTS and CTS packet exchange are proposed to improve the channel reuse ratio of the network. An optimal transmission power selection scheme based on the load condition in the network is presented in [Park and Sivakumar 2002]. Similarly, transmission power control schemes to increase the network throughput by controlling the number of hops in multi-hop packet delivery are also discussed in [Gomez and Campbell 2004; Li and Sinha 2003; Monks et al. 2001]. Recently Lin et al. [Lin et al. 2006] proposed an adaptive transmission power control (ATPC) protocol which is designed based on the empirical measurements and provides per-link transmission power control similar to our power control protocol [Son et al. 2004]. Proposed protocol reacts to the temporal change of the link quality with explicit on-demand feedback packets.

Main differences between the most of related work (except the recent work [Lin et al. 2006] which shares the similar methodology and objective as our prior work [Son et al. 2004]) and our study in the effect of transmission power control are as follows. First of all, our study is based on the testbed experiments rather than based on theoretical study or simulations. Secondly, the focus of our research is primarily on link quality control which as we show leads to important benefits in terms of energy consumption and delivery rates.

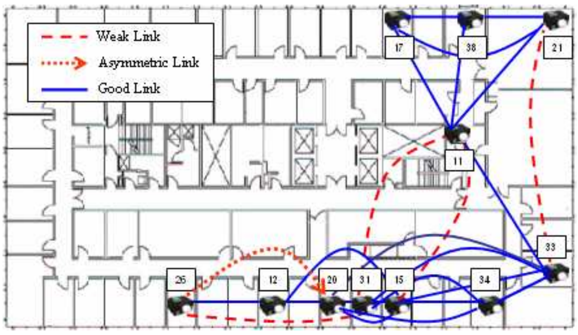


Fig. 1. PC104 Testbed at USC/ISI and a snapshot of weak, asymmetric, and good links

3. TRANSMISSION POWER CONTROL ON A SINGLE WIRELESS LINK: EXPERIMENTAL STUDY

In this section, we will identify the aspects of low power RF wireless links that make many previously proposed power control schemes difficult to implement in practice. We perform systematic experiments on single wireless links varying several key parameters under different transmission power levels.

3.1 Experiment Methodology

The link quality measurements in our testbed show inconsistent link qualities for some links within the transmission range. To identify the cause of this discrepancy and the effects of transmission power change on the wireless link, we perform systematic experiments varying some key parameters presumably related to the wireless link quality: hardware difference, distance between the transmitter and receiver, locations of the nodes, and time (i.e., surrounding environment change).

Our link quality experiments are performed on a Stargate [I-LENSE b] testbed with Mica2 motes which use CC1000 [Chipcon] radio operating at 433 MHz as a RF transceiver. The Emstar [Girod et al. 2003] software platform is used for our experiments and data collection.

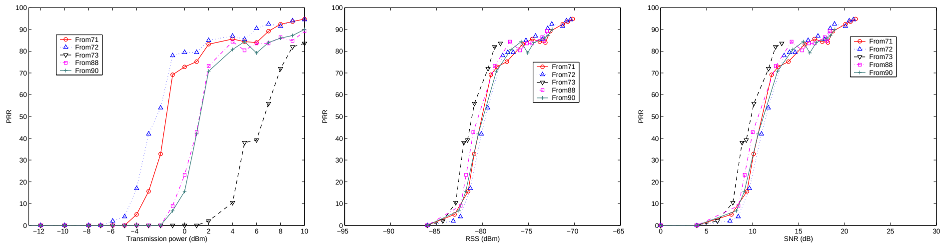
Experiment results present both packet reception rate (PRR) and received signal strength (RSS) at the receiver given transmission power level at the sender. These statistics are based on 50 packet experiments.

Thirteen different transmission power levels range from -13 to 10 dBm are tested in the indoor environment. We also vary node positions and the link distance between the transmitter and receiver for some experiments. The link distance between the transmitter and receiver is varied between 6 m and 20 m distance, and we present some selected distances which show interesting results.

3.2 The Effects of Unreliable Wireless Links and Tx Power control

Figure 1 shows a snapshot information of the link quality in packet reception rate (PRR) for every link in our PC104 [I-LENSE a] testbed. We define two types of unreliable links with PRR metric: *weak links* and *asymmetric links*.

In our testbed, every pair of PC104 nodes are connected through a reliable communication route, in which every communication link is classified as a good link.



(a) Tx Power to PRR (b) RSS to PRR (c) SNR to PRR

Fig. 2. Effects of transmitter hardware change. Five different transmitters to the same receiver.

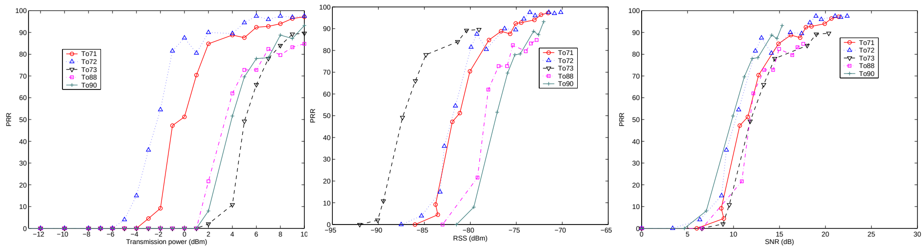
However, it is often the case that unreliable links are utilized instead of good communication links and the throughput of the network is badly affected in our testbed experiments with two variants of the directed diffusion [Heidemann et al. 2003; Intanagonwiwat et al. 2000] routing protocols. The end-to-end packet delivery rates with single data flow (at the same experiment setting as Section 4.4) range between 43 to 58 % with one phase pull diffusion and 72 to 83% with two phase pull diffusion experiments without any link quality control scheme. One phase pull diffusion routing shows lower PRR due to its symmetric link quality assumption which is not always valid in real world.

As the experiment results show, having unreliable links is worse than having no links at all when bi-directional communication is required and there is a good communication route to use between two nodes: Unreliable links need to be either converted to good links or prevented from the use.

Even though the increased transmission power level elevates the quality of wireless links, it comes with some side effects. First, increased transmission power may generate new weak links with increased signal strength that is not yet enough to build new reliable links. A blacklisting approach is merged together with our proposed transmission power control scheme to address this problem. Secondly, increased transmission power uses up more network capacity. There is a trade-off between the improved link quality and reduced network capacity. However, our proposed transmission power control scheme does not always increase the transmission power. For the links that can provide the same reliable communication at lowered transmission power level, it reduces the transmission power and that can decrease the interference to the network. Our transmission power control scheme is proposed considering these two identified side effects as well as the benefits of transmission power control.

3.3 Different Transmitters

To see the effect of the transmitter hardware difference on the wireless link quality, we measured link qualities from five different transmitters to a same receiver. Every transmitter uses the same software settings and sends packets from the exact same location to the static receiver. Both transmitter and receiver are located in the hallway of the building. The link distance between the transmitter and receiver is 20 m and we measure the link qualities in both PRR and RSS metric at the receiver



(a) Tx Power to PRR (b) RSS to PRR (c) SNR to PRR

Fig. 3. Effects of receiver hardware change. Same transmitter to five different receiver.

for each transmitter varying the transmission power.

From the experiment results shown in Figure 2(a), we can see that the link quality at the receiver becomes quite different for different transmitters even at the same node location at the same output power level. When we plot the relationship between the measured RSS and PRR in Figure 2(b), we can see that RSS to PRR relationship is similar for the five different transmitters. From this experiment result, we can see that the the different link quality observed in PRR metric in Figure 2(a) comes from the different output signal strength from different transmitters (i.e., hardware non-ideality) at the same transmission power setting. Figure 2(c) shows the signal-to-noise-ratio (SNR) to PRR relationship. The noise level at the same receiver is about the same and the graph looks very similar to RSS to PRR relationship other than the changed x-axis unit.

The PRR differences in transitional (or gray) area identified in prior studies [Cerpa et al. 2003; Ganesan et al. 2002; Zhao and Govindan 2003] are related to this hardware non-ideality issue because this can be the factor that distinguishes link qualities at low transmission power level as the Figure 2 shows. From these experiments, we can see that the transmission power level cannot be a good estimator of link quality due to hardware variance, and the level of link quality difference observed in real world is closely related to the selected transmission power level.

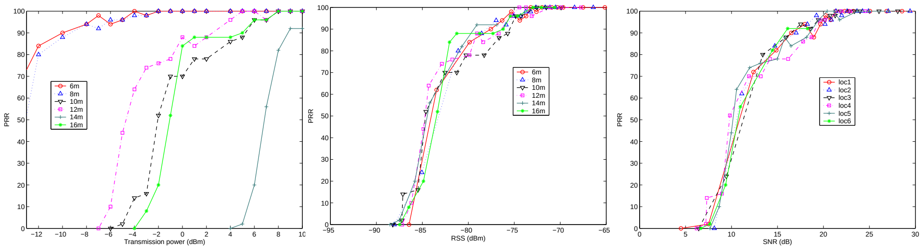
3.4 Different Receivers

We also investigate the effects on the link quality when different nodes are placed as packet receivers. We use the exact same transmitter and receiver positions with 20 m link distance as our previous experiments with transmitter change. Five different receiver nodes are tested with a same transmitter.

Figure 3(a) shows that link quality changes for different receiver nodes even the same transmitter transmits at the same output power level. RSS to PRR relationship shown in Figure 3(b) still shows big difference for different receiver nodes. This is because the difference is not coming from the transmitter side.

When we compare the SNR to PRR relationship in Figure 3(c), there is much smaller difference among different receiver nodes. Therefore, we can see that the observed differences in link qualities at different receiver nodes can be attributed to the different level of ambient noise at the receiver.

In Figure 2(a) and 3(a), the area in the transmission power range between -6



(a) Tx Power to PRR
(b) RSS to PRR
(c) SNR to PRR

Fig. 4. Effects of link distance change

and 10 dBm shows high variation of link qualities. In this transmission power range, the quality of each link is different at the same transmission power level and the different transmission power is required for each link to reach the same PRR level. We call the range of transmission power that generates this kind of variation *unreliable transmission power range*. Outside (either higher or lower side) of the *unreliable transmission power range*, the link quality is the same regardless of the selected transmission power level.

The link quality difference observed in *unreliable transmission power range* can be avoided by transmission power control in two ways. First, by assigning the same transmission power outside of the unreliable transmission power range. Second, by assigning a distinct transmission power for each link to provide a desired link quality level.

From the experiment results, we can realize that the transmission power level or the measured received signal strength (RSS) level can not be an accurate link quality estimator for different hardware. We can explicitly measure PRR with multiple packets or use the SNR and PRR pair of information together for a better and efficient link quality estimation.

3.5 Wireless Link Distance (Path Loss)

We present the effects of the wireless link distance and transmission power change on the link quality in this section. Experiments are performed in the hallway of the building where a clear line of sight is available between the transmitter and receiver.

As the experiment result presented in Figure 4(a) shows, PRR changes as the link distance and transmission power level change. The order of link distance that shows better PRR at the same transmission power level is 6 m, 8 m, 12 m, 10 m, 16 m, 14m while this order changes among 10m, 12m, 16m distances at different transmission power levels.

The effect of path-loss can be observed at a relatively coarse granularity even thought the order is not linear to the link distance: closer distance (6m, 8m) show clearly better link quality than longer distance (14m, 16m). The non-linear link quality order in our experiment results can be attributed to the severe indoor multi-path effect. When we plot the RSS to PRR and SNR to PRR relationship in Figure 4(b) and 4(c), we can confirm that RSS as well as SNR is a good link quality estimator for the same hardware pair. Experiment results show that link

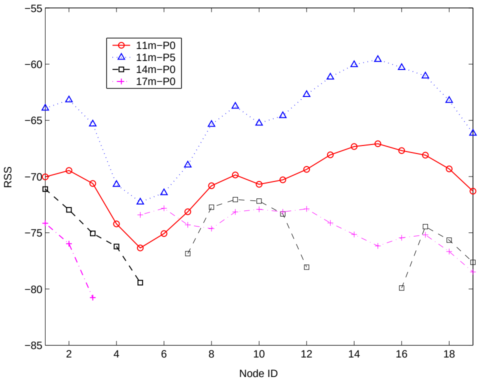
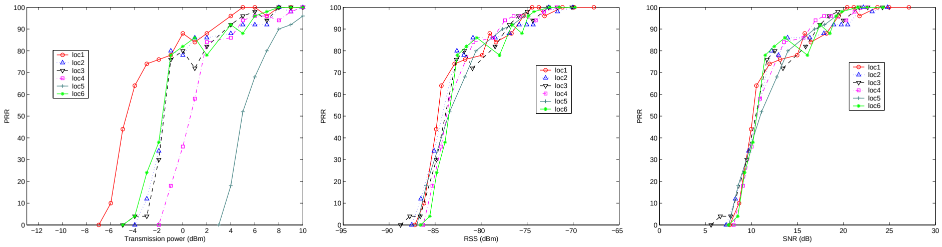


Fig. 5. RSS change at 19 different receiver positions at around 11,14,17m distance between the transmitter and receiver. The transmitter uses 0 (and 5 only for 11m) dBm transmission power (P0)



(a) Tx Power to PRR (b) RSS to PRR (c) SNR to PRR

Fig. 6. Effects of node location change

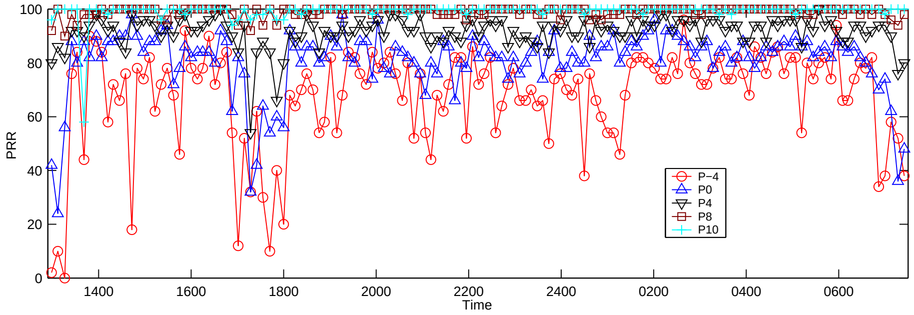
distance is not an accurate link quality metric.

3.6 Node Location (Multi-Path)

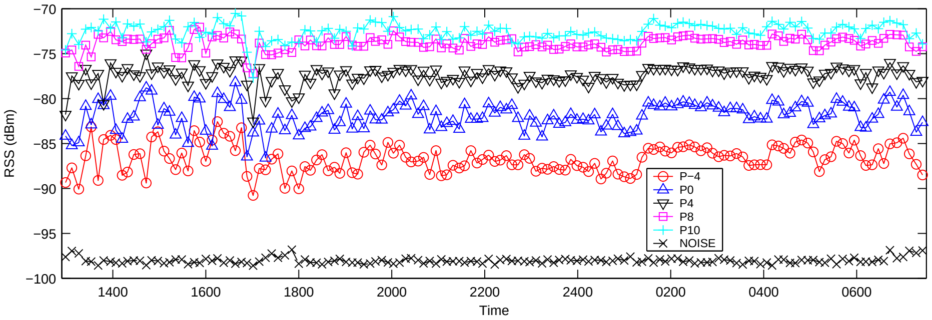
To better understand the effects of node location and to see if how severe the multi-path effect is, we performed a series of link quality measurements in the hallway of the building.

We placed a transmitter in the middle of the hallway and measured a link quality in both PRR and received signal strength (RSS) at the receiver located at around 11, 14, 17m distance from the transmitter. At each of these three chosen distance, we draw a perpendicular line (about 147cm long) connecting two walls of the hallway and performed experiments placing the same receiver at 19 different locations from the leftmost position 1 to the rightmost position 19 (at every 7.5 cm interval) on this line.

Figure 5 shows that even for the links at around the same distance (i.e., on the same line), the RSS changes depending on the specific node positioning. The measured range of RSS on the same line (i.e., $RSS_{max} - RSS_{min}$) was between 7.9 and 12.7 dBm in the four experiments results presented in this figure. Due to this severe link quality variation caused by the multi-path effect, we could even have a better



(a) Link quality (in PRR) change over time



(b) Received signal strength (RSS) and noise level change over time

Fig. 7. PRR, RSS and noise level change over time at different transmission power levels

link quality at 17 m distance than 11 m distance at the same transmission power level (0 dBm in this example) at some combination of receiver node placements. (e.g., when two receivers are placeed at the position 5 of 11m and 17m distance.)

When we compare the RSS change at 0 and 5 dBm transmission power at 11 m distance, we can clearly see the improvement of the link quality with increased output power. However, the measured value shows the RSS improvement varies between 3.51 and 7.49 at 19 different positions at the same amount of transmission power change.

Figure 6 shows a similar experiment results at 10 m link distance. A new pair of sender and receiver node is used and the receiver is placed at six different node location on the same line at two inch intervals. We can see wide variation of link qualities between -7 and 8 dBm transmission power levels.

From these results we can realize that (1) The multi-path effects are severe in indoor in both cases with a line of sight link between the transmitter and receiver (2) severe link quality variation can be expected with small movement of sensor nodes with low-power wireless links (3) we can expect significant link quality improvement in terms of PRR with small increase in transmission power for the links in the unreliable transmission power range (4) The effect of transmission power control (i.e., the change of RSS at the receiver) varies with different hardware (i.e.,

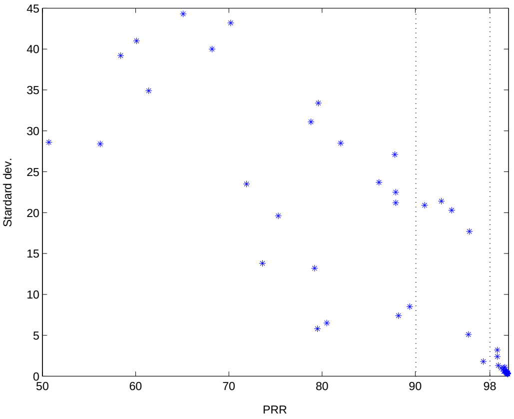


Fig. 8. Standard deviation change for different PRR value

PRR	60-70	70-80	80-90	90-100
STDEV	40.5	23	18.8	3.4
PRR	90-95	95-98	98-99	99-100
STDEV	19.8	10.8	2.2	0.89

Table II. Standard deviations for the links with different levels of PRR

transmitter and receiver pair) and different node location.

3.7 Time

We continuously measured the link quality of the testbed for 18 hours between 13:00 pm and 7:30 am to see the change of link quality over time. Packet reception rate (PRR), received signal strength (RSS) and ambient noise are measured every eight minutes with 50 packets between -4 and 10 dBm transmission power levels.

Figure 7 presents link quality snapshots of communication link ($LINK_{72->91}$) in the Stargate testbed (shown in Figure 11). We can clearly see high variations in the link quality at the same transmission power level. Especially, there is much high variation in link quality (both in PRR and RSS) during the daytime between 14:00 and 18:00 than the night time between 2:00 and 6:00. The dynamic changes in surrounding environment during the daytime causes much severe link quality variation.

When we compare the link quality variation between the cases with different transmission power levels in Figure 7(a), we can see that the level of link quality variation is higher at different transmission powers. When we use the transmission power level outside *unreliable transmission power range* (e.g., transmission power of 8 dBm), this link can be converted to a reliable link regardless of the time change. Even at the high transmission power level, the change in RSS is similar to the low power cases as shown in Figure 7(a). However, the PRR is less sensitive to the RSS variation at this level of signal strength and can tolerate dynamic environmental change with the extra received signal strength than required for reliable communication.

3.8 Selecting a Transmission power level

Figure 8 and Table II show the link quality variation for the links with different PRR levels in our seven day measurements in the testbed. We can see that the links with lower than 90% PRR shows very high variation in link quality. When we take a closer look at the links with higher than 90% link quality, the links with lower than 98% PRR still shows relatively high quality variation. It is because the value is still within the unreliable transmission power range where a small signal strength change can significantly affect the link quality. Experiment results imply that it is better to use only links with higher PRR close to 100% for a consistent link quality.

However, a blacklisting only approach without transmission power control scheme often chooses 80% or 90% PRR as a *blacklisting threshold* (BL_θ) value because it is not reasonable to use a higher than this threshold and throws away still usable links below the selected BL_θ. Therefore, it suffers from the frequent link quality change. Fluctuation in link quality around the blacklist threshold (BL_θ) may result in frequent topology change that can harm the performance of upper layer protocols.

With transmission power control scheme, it is feasible to use higher blacklisting threshold (e.g., 98% or even 100% PRR) because converting moderate quality links to good, reliable links is often achievable with even small transmission power increase.

We have used a packet reception rate (PRR) as a metric to estimate a link quality and collected a PRR at every transmission power level, and proper transmission power level is selected based on the measured PRR at different transmission power levels. However, it is hard to evaluate link quality in PRR metric due to the high overhead of PRR measurement for each link. If the received signal strength (RSS) information is available at the receiver, we can use the RSS information to maintain proper link quality easily and quickly in response to the environmental change.

The measured RSS is a good indicator of the link quality for the same receiver (as we discussed in this section) and the PRR is expected to be proportional to the measured RSS within some variation range.

4. TRANSMISSION POWER CONTROL WITH BLACKLISTING

Based on the experimental observations, we introduce a new transmission power control mechanism.

4.1 Key Characteristics and Benefits of our proposed scheme

We propose a transmission power control scheme with following key characteristics.

(1) Transmission power control for link quality control:

The primary purpose of transmission power control is to provide reliable communication links to the link users. Every communication including broadcast as well as unicast is always using reliable links which meets user's requirement and expectation. PCBL can ensure reliable bi-directional communication links and the collision avoidance scheme implemented based on RTS/CTS handshakes could perform better by eliminating asymmetric and weak links.

(2) Packet-based transmission power control:

A proper transmission power can be assigned to each packet based on the destination and type of the packet considering link quality requirement (i.e., link quality control threshold: LQ_θ). We can expect reduced energy consumption in packet transmission by using minimum transmission power which meets LQ_θ for each packet transmission. The reduced interference from minimizing the transmission power for each communication can improve the spatial reuse of the network as well. We can also provide customized reliability to the packets with different importance.

(3) Metric-based link quality estimation:

Link quality is empirically measured based on the packet reception rate (PRR) metric rather than distance-based link quality approximation. While we could realize that the link distance is not an accurate metric of link quality in our experimental study and other previous empirical studies, PCBL utilize PRR metric empirically measured at different transmission power for different links to reflect the diverse link qualities even at the same link distance in real world.

If received signal strength (RSS) information is available, (RSS,PRR) pair information can be used together with transmission power level for more efficient and faster link quality estimation and corresponding control.

(4) Blacklisting at adjusted transmission power level:

Not every link can be converted to a good link with transmission power control even at the maximum transmission power level. Even new weak or asymmetric links can be generated at adjusted transmission power level. We combine link blacklisting approach together with transmission power control scheme to avoid the use of remaining unreliable links at new transmission power control even for the broadcast packet. Both link-based and packet-based blacklisting schemes will be discussed.

4.2 Basic PCBL Algorithm: Optimization Prior to Routing

We explain the basic steps of implementing our proposed transmission power control with blacklisting scheme (PCBL). Brief algorithm is presented in Table III.

First of all, each node measures the quality of links to its neighbor nodes in PRR metric for all (or pre-selected) transmission power levels $P = \{P_{min} \leq P_i \leq P_{max}\}$, where i is a transmission power in dBm. $PRR(r)_{P_i}$ denotes the PRR at the output power of i dBm at the receiver node r. At the receiver, it records the RSS value for each transmission power level from each sender.

To select a unicast transmission power level, a link quality control threshold value (LQ_θ) in PRR metric need to be selected according to the required level of link reliability (e.g., $LQ_\theta \leftarrow 0.95$). Simply, a common LQ_θ value can be used for every link, or each node can use different LQ_θ values for different links or even for different type of packets based on the importance of each packet communication. The minimum transmission power which satisfies the LQ_θ is assigned for each link (i.e., for each receiver r) or for each packet type as a unicast transmission power: $Utx_r =$ min P_i, which meets $PRR(r)_{P_i} > LQ_\theta$. Otherwise, $Utx_r = P_{max}$.

Based on the required link reliability and the intended connectivity level, PRR-based blacklist threshold (BL_θ) is selected. PCBL can use either a link-based blacklisting or packet-based blacklisting scheme.

The *link-based blacklisting* blacklists every link with lower PRR than BL_θ and

Step 1: Collect link statistics in PRR metric at every selected transmission power level

Step 2: Select a unicast transmission power for each link (i.e., for each one hop neighbor) which minimize energy consumption while providing required link reliability

Step 3: Blacklist remaining or new unreliable links after transmission power control

Step 4: Select a broadcast transmission power for each node with the maximum unicast transmission power level

Table III. Brief PCBL algorithm

determines the topology of the network which is common to the every application. Each link can select a different BL_θ for further optimization if necessary. However, the *packet-based blacklisting* uses adaptive BL_θ value for each packet (e.g., based on the type of the packet or the type of application) rather then for each link in the network. The packet-based blacklisting is necessary when the requirements for the link qualities are different for each application or for each type of packet. This can provide a better utilization of the network.

LQ_θ is used to control the quality of the link and BL_θ is employed to ensure the minimum reliability of the link. LQ_θ should be greater than equal to BL_θ and the gap between LQ_θ and BL_θ reduces the variation of the link availability which may lower the performance of upper layer protocol from the frequent change of the network topology during the operation.

In the last step, each node (i) selects a broadcast transmission power (Btx_i) with the maximum unicast transmission power assigned in step 2 (but excluding the unicast power of the links blacklisted in step 3): $B_i = \max Utx_r, \text{for } \forall$ neighbor r. This ensures each sender transmits broadcast packets with enough transmission power to reach every neighbor node which meets required link quality threshold (i.e., higher PRR than BL_θ).

Our goal in transmission power control is to assign a minimum transmission power that provides required link quality for each packet transmission and also to remove the negative effects caused by unreliable links. Close to the optimal transmission power setting that achieves our purpose can be identified for each link (i.e., unicast) and for each node (i.e., broadcast) based on the collected link statistics information at different transmission power levels. Selected transmission powers satisfy the required link quality and also minimize the interference to the network. Changed transmission power level can expose new links that are not visible at default transmission power. The unreliable links that cannot be converted to good links even with transmission power control and newly generated weak and asymmetric links at changed transmission power levels are blocked from the use with incorporated blacklisting scheme.

4.3 On-demand transmission power optimization for each long-lived communication

Collection of link statistics before the start of each data communication is unacceptable for some application where the prompt delivery of collected information is critical. Keep maintaining up-to-date link quality information for every links in the

```
Step 1: Collect link statistics only at the maximum transmission
   power level ($P_{max}$)
Step 2: Blacklist unreliable links before finding a routing path
Step 3: Find a delivery path between the source and sink with
   a chosen routing protocol
Step 4: Identify unicast transmission powers to use only for
   the links in the delivery path
```

Table IV. PCBL algorithm for a long-lived communication

network to promptly start actual data communication is unnecessary and inefficient when the frequency of the communication is very low.

A different transmission power control approach can be taken to reduce the delay and overhead from the link statistics collection stage and a brief algorithm is presented in Table IV. We can collect link statistics only for the links participating the packet communication between the given source and sink. With this modified approach, each node converges to a close to optimal transmission power level after a reliable routing path is set up by a routing protocol with small prior link statistics collection efforts.

When we find an optimal unicast power level for each link, we can collect the link quality during the idle data communication period or we can lower the transmission power from the P_{max} to the lower level and decide proper transmission power level based on the number of retransmission experienced at each transmission power level.

4.4 Experiment Results for a Single Data Flow

The performance of proposed transmission power control with blacklisting scheme is evaluated in the PC104 testbed shown in Figure 1. Even though we used relatively small, manageable number of nodes for our experiments, this testbed satisfies our experimental condition as it still carries many unreliable links. Larger size testbed experiments which involves larger number of hops for packet delivery. Additional hops increases the probability of including unreliable links in the delivery path and it is expected to see even further performance drop in multi-hop packet communication without any link quality control scheme.

In our experiments, two nodes located farthest in the testbed are selected as a packet sender (node 21) and a receiver (node 26). Directed diffusion [Intanagonwiwat et al. 2000] is used as a routing protocol and fully active mode S-MAC [Ye et al. 2002] is used as a medium access control protocol.

The following eight scenarios categorized based on five different transmission power control schemes are compared in this experiments: (1) *OPP-P0 and TPP-P0*: One Phase Pull (OPP) and Two Phase Pull (TPP) diffusion routing at default transmission power of 0 dBm (2) *OPP-P5 and TPP-P5*: OPP and TPP routing at increased transmission power of 5 dBm (3) *OPP-P10 and TPP-P10*: OPP and TPP at the maximum transmission power of 10 dBm (4) *M-BL*: TPP with Blacklisting at the maximum transmission power level (i.e., 10 dBm) and finally, (5) *PCBL*: TPP with our proposed transmission power control with blacklisting scheme. We

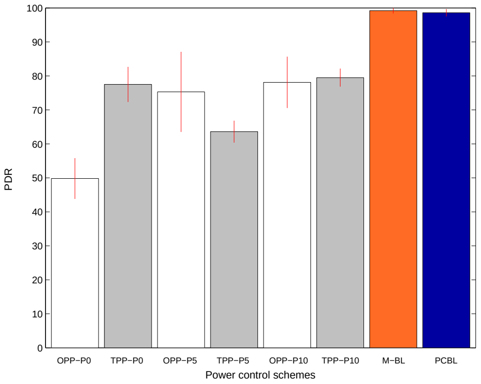


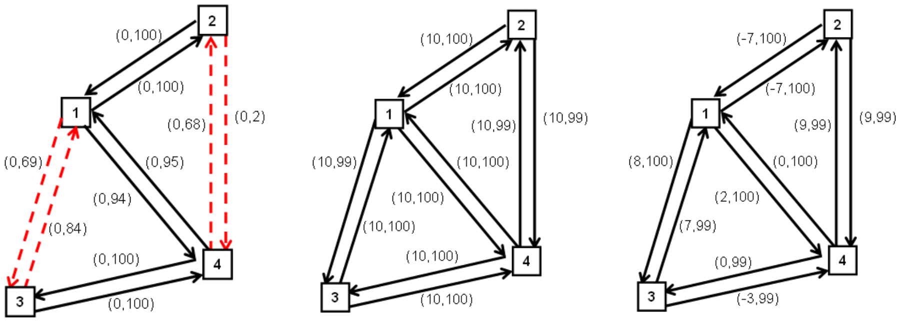
Fig. 9. Packet Delivery Rate from the experiments with five different power control schemes

set LQ_θ to 98% PRR and BL_θ to 90% PRR in this experiment. We perform experiment with only TPP for M-BL and PCBL schemes because both schemes remove asymmetric links and OPP and TPP are expected to perform equally in terms of PRR when there is no asymmetric links. The experiment results show average end-to-end packet delivery rate (PDR) over five 1200 seconds experiments.

Figure 9 presents PDRs measured from the eight different testbed experiments. Error bars show standard deviation values. First, we want to see if how much improvement we can expect in multi-hop packet communication by increasing the default transmission power of each node instead of using distinct transmission power for each link or for each packet. When we compare the PDRs for OPP diffusion at different transmission power levels, we can see that PDR gets higher at the higher transmission power level. Improvements from 0 to 5 dBm change was mainly coming from the increased link quality of previously weak link that was utilized in the packet delivery in both scenarios. However, the improvement is negligible when the default transmission power was increased from 5 to 10 dBm, which is the maximum available output power.

When we compare the performance betwen OPP and TPP at 0 dBm transmission power, TPP shows higher PDR because it avoids using asymmetric links that OPP diffusion selected as a part of the routing path. At the increased transmission power of 5 dBm, PDR even gets worse due to new unreliable links generated at this power level are utilized by the routing protocol. At the maximum transmission power level, TPP shows about the same PDR as with 0 dBm transmission power and still loses about 21% of the total packets.

The PDR in directed diffusion is highly dependent on how reliable delivery route is built for packet delivery. In the wireless network which only uses a single hop data communication, simply increasing the default transmission power is an effective way to improve PDR. In a multi-hop wireless data communication, whether the unreliable wireless links exist or not is an important factor which decides the reliability of data communication. Increasing default transmission power can convert some of the weak and asymmetric links to reliable links and help to discover new links which was not available at lower transmission power level, but it is not an



(a) without Tx power control (b) with M-BL scheme (c) with PCBL scheme

Fig. 10. Topology changes with different power control schemes: a solid arrow represents a realiable link with over 90% PRR and a dotted arrow represents a link with $0 < \text{PRR}(\%) < 90$. Each link is also marked with corresponding (transmission power, observed PRR) pair information

Difference	Unicast	Broadcast	Total	Per Packet
M-BL	+75.4%	+53.2%	+67%	+66.2%
TPP-P0	+3.5%	-40.3%	-13%	+10.8%

Table V. The energy consumption difference in packet transmission compared to the PCBL scheme

effective way to improve PDR in most cases because (1) it may not convert every unreliable links to reliable links and may also generate new unreliable links at new transmission power level, and (2) it uses up more network capacity at increased transmission power level.

TPP with M-BL and TPP with PCBL result in close to 100% packet delivery rate: 99.2% and 98.7% respectively. Both schemes provide comparable link qualities at adjusted transmission power levels. Therefore, the same links are blacklisted and most likely both schemes generate the same network topology. Figure 10 shows a simplified four node example from the testbed that visually compares the links under three different schemes. The main differences between PCBL and M-BL are found in (1) the amount of energy consumption and (2) the level of interference in packet transmission.

We compare the energy consumption in packet transmission between the PCBL scheme with the case without any power control scheme (i.e., TPP-P0) and also with the case with M-BL scheme in table V. Energy consumed for every broadcast (control packets sent by the routing protocol) and unicast packet (data packet) transmissions are summed for TPP-P0 and M-BL schemes and compared against our PCBL scheme. Control packets used by MAC layer protocol (i.e., RTS, CTS, and ACK) are excluded from the calculation.

In our testbed experiments with single data flow, M-BL scheme shows 67% more energy consumption than PCBL and both unicast and broadcast packets used up much more energy than PCBL because it transmits every packet at maximum transmission power. Original TPP scheme (TPP-P0), which transmits packets at

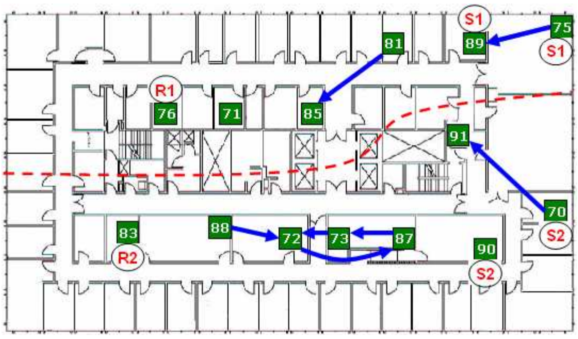


Fig. 11. Stargate node locations for the multiple data flow experiments.

Expr No.	Flows A	Flows B	Description
1	89 $\leftarrow$ 75	72 $\leftarrow$ 73	low interference
2	91 $\leftarrow$ 70	72 $\leftarrow$ 73	medium interference
3	85 $\leftarrow$ 81	72 $\rightarrow$ 87	one flow gets stronger interference
4	73 $\leftarrow$ 87	88 $\rightarrow$ 72	strong interference

Table VI. Four experiment scenario comparison

default power of 0 dBm, consumes 13% less energy than PCBL scheme. When we compare energy consumption for each successful packet delivery, however, PCBL saves 10.8% transmission power compared to TPP-P0. This shows an example of the compensation gained from the increased network reliability that exceeds the extra energy consumption in packet transmission.

4.5 Experiment Results for Multiple Data Flows

In a single flow packet communication experiment, both PCBL and M-BL perform great in terms of packet delivery rate. To see the effect of over-amplified transmission signal from M-BL scheme, we performed experiments with multiple data flows in this section.

First, we have run four node experiments with two concurrent data communication flows (called flow A and B) in our Stargate testbed (shown in Figure 11). Two packet senders are synchronized to start the packet transmission and continuously transmit packets one after another. PCBL and M-BL schemes are tested with turning on and off the collision avoidance functionality. In this experiment, we use 100% PRR for LQ_θ and 90% PRR for BL_θ in this experiment for PCBL scheme. We repeat experiments with four different sender and receiver node pairs (i.e., four different pairs of data flow) as shown in Figure 11 and described in the table VI. Different node locations changes the signal strength at the receiver and the level of interference between the flows. We repeat experiments five times for each setting and each result shows the mean value. Due to the non-linearity in the measured signal strength value at the higher than -55 dBm level, we used estimated RSS value based on the output power level for SNR and SINR calculation for the values measured in this region. Other than this four node experiments, we also

Experiment		PCBL		MBL	
w/CS		flow A	flow B	flow A	flow B
1	data rate (pkts/sec)	**6.7**	**6.5**	**3.9**	**3.9**
	SNR (dB)	33.47	40.15	50.97	49.79
	PRR (%)	100	100	100	100
2	data rate (pkts/sec)	**5.57**	**5.29**	**3.71**	**4.51**
	SNR (dB)	27.57	38.4	39.13	49.83
	PRR (%)	100	100	100	100
3	data rate (pkts/sec)	**4.42**	**4.33**	**3.54**	**4.08**
	SNR (dB)	27.11	27.5	29.35	42.38
	PRR (%)	100	100	100	100
4	data rate (pkts/sec)	**2.94**	**3.33**	**3.78**	**3.77**
	SNR (dB)	29.35	31.08	42.59	43.91
	PRR (%)	100	100	100	100

Table VII. PCBL and M-BL comparison with a collision avoidance

performed supplementary experiments on the larger size testbed.

4.5.1 *PCBL vs M-BL with a collision avoidance scheme.* We enabled a collision avoidance scheme in S-MAC [Ye et al. 2002] which is a carrier sensing followed by a RTX/CTS/DATA/ACK sequence in this experiment.

Table VII compares the experiment results between the PCBL and M-BL. The collison avoidance scheme prevents packet collisoin by disallowing concurrent packet transmission within the same channel. Therefore, the PDR is always 100% for both PCBL and M-BL. However, additional packet sender and receiver in the same channel compete for the limited bandwidth and reduce the throughput of both data flows. Each additional active sender or receiver occupies the channel by deferring any other packet transmission with RTS or CTS packet transmission when we use a collision avoidance scheme.

When there is no competing packet sender, a sender could transmit 6.7 data packets (excluding control packets) per second in our experiments with 230B data packets. The Experiment 1 results show close to 6.7 packets per second throughput for both flows with PCBL scheme. In other words, there was almost no interference coming from the other flow and concurrent packet communication was possible with PCBL in this case. However, the throughput for M-BL in Experiment 1 was 3.9 packets per second. This means the data and control packet communications from the other flow caused interference (i.e., share the channel together) and lowered the throughput of communication links.

As we change the node location from Experiment 1 to Experiment 2, the level of interference between the two flows are increased. The strength of interference (i.e., the signal strength of the data and control packet transmitted from the other flow) is important even when the collision avoidance scheme is turned on because it changes (1) the probability of the control packet reception and (2) the probability of a packet collision when the control packet is lost and concurrent packet transmission is not prevented.

Depends on the number of competing sender and receiver nodes and the quality of signals from these nodes in the same channel, the throughput of each link changes. As the table VII shows the throughput of the PCBL drops as the interference from

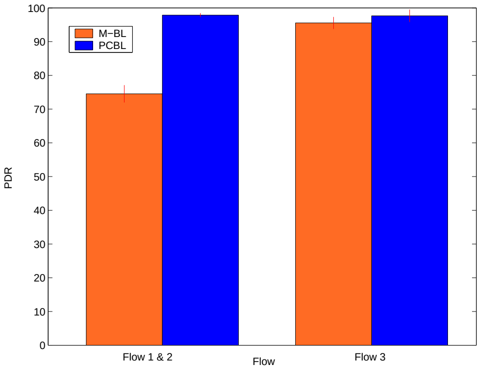


Fig. 12. Packet Delivery Rate from the experiments with three data flows

the other flow increases. However, the throughput of the M-BL does not change much with experiments at four different locations. The extra transmission power used in M-BL help the delivery of the control packet to the other flow and prevent most of the concurrent packet transmissions.

With a collision avoidance scheme, interference only increases the delay of the packet communication instead of causing a packet lost from the collision. However, when multiple senders compete for the same channel for a long period of time, the delayed transmission can lead to the packet drops from the queue overflow. We performed another multi-hop packet communication experiments with multiple continuous data flows in the testbed (shown in Figure 1). Three data flows are involved in this experiment. Node 17 and 38 send packets to node 33 (flow 1&2) and node 20 sends packets to node 12 (flow 3) at 1 packet per second send rate for 700 seconds.

Figure 12 presents experiment results based on the five repeated experiments. This figure shows the PDR for flow 1&2 and flow 3 under different power control schemes. The standard deviation from repeated experiments is marked with an error bar. PDR in flow 3 are similar for both schemes: 97.9% for TPP with M-BL and 97.6% for TPP with PCBL. The PDR for flow1&2, however, shows 21% difference in favor of TPP with PCBL: 95.5% for PCBL and 74.5% for M-BL. Packets from node 17 and 38 are all delivered through node 11 and the wireless channels around node 11 involves four times more traffic than the traffic between node 20 and 12. The interference from over-amplified transmission power in M-BL saturates the wireless channel around node 11 and cause more packet drops with M-BL in flow 1 & 2 while flow 3 could still get enough channel access with both schemes.

The collision avoidance scheme can prevent packet collisions, but the stronger interference from M-BL use up more channel capacity and builds up the queue size and ends up with packet drop from queue overflow. Therefore, even with the collision avoidance scheme, interference can still affect the delivery ratio of the packet from the inefficient spatial reuse of the network.

Experiment w/o CS		PCBL		MBL	
		flow A	flow B	flow A	flow B
1	data rate (pkts/sec)	13.7	13.7	13.7	13.7
	SINR (dB)	33.47	40.15	36	32.63
	PRR (%)	**100**	**100**	**100**	**100**
2	data rate (pkts/sec)	13.7	13.7	13.7	13.7
	SINR (dB)	27.57	38.4	13.83	31.63
	PRR (%)	**100**	**100**	**100**	**100**
3	data rate (pkts/sec)	13.7	13.7	13.7	13.7
	SINR (dB)	9.56	12.16	-2.68	25.47
	PRR (%)	**92.7**	**90**	**0**	**100**
4	data rate (pkts/sec)	13.7	13.7	13.7	13.7
	SINR (dB)	-1.62	2.36	3.29	-0.70
	PRR (%)	**0**	**0**	**100**	**0**

Table VIII. PCBL and M-BL comparison without a collision avoidance

4.5.2 *PCBL vs M-BL without a collision avoidance scheme.* We disabled every collision avoidance scheme including the carrier sensing in the experiments presented in this section. This allows for a sender to transmit packets even when it hears a on-going packet communication in the same channel. In other words, concurrent packet transmission is always allowed in the same channel. We can compare the performance of PCBL and M-BL scheme in the situations where the interference from each communication can influence the communication of others.

There is no difference in packet send rate (packets per second) for different schemes and different flows in this experiment because each sender can transmit a packet anytime regardless of the channel condition without collision avoidance scheme. Therefore, the send rate is about twice faster than the case with a collision avoidance scheme in our experiment.

Table VIII shows the PRR together with signal-to-interference-plus-noise-ratio (SINR) rather than SNR because there exists an interference from the other flow. We can see that SINR value becomes lower as the distance between the two flows gets closer. Overall, higher number experiments experience higher interference from the other flow and therefore present lower SINR values. When the level of interference is relatively low like the Experiment 1 and 2, the intended sender's signal strength is much stronger than the interference from the sender in the other flow. As the experimental study proves [Son et al. 2005; Whitehouse et al. 2005], stronger signal could be delivered under the concurrent packet transmission situation and both Experiment 1 and 2 shows 100% packet reception rate for both PCBL and M-BL for both flows. This phenomana is called *capture effect* [Whitehouse et al. 2005].

In Experiment 3, flow A and B are placed in a roughly parallel position while the receiver of the flow A is somewhat closer to the sender of the flow B. With PCBL, both receivers get much stronger signals from each sender and provide reliable concurrent communication for both flows. When the M-BL scheme change sender's transmission power to the maximum level, the interference strength from the sender in flow B (i.e., node 72) becomes even stronger than then signal strength from the intended sender in flow A (i.e., node 81). The SINR at the receiver node 81 becomes

	PCBL		MBL	
PDR	w/ CA	w/o CA	w/CA	w/o CA
flow 1 (%)	53	67	54	34
flow 2 (%)	45	53	37	46
AVG (%)	49	60	45	40

Table IX. PCBL and M-BL comparison with a collision avoidance

negative and no packet can be successfully delivered for flow A. However, the packets in flow B can be reliably delivered because the sender in flow A is located much further than the intended sender of flow B.

When both flows are located very close like the Experiment 4, there is high probability that the interference strength from the other flow is strong enough to disturb the intended packet communication even with PCBL scheme which causes less interference than M-BL. With PCBL, neither flow could successfully deliver packet to the receiver. With M-BL, the interference strength is even higher than the case with PCBL on each other's data flow. The SINR at the receiver of the flow B becomes negative and the PRR of the flow B becomes zero. However, the signal strength from the sender in flow A is even stronger than the high interference from flow B and it can capture the channel at the maximum transmission power level of both senders in this case. This is a special example of the benefits of extra signal strength from over-amplified transmission power level. However, this is coming from the fact that the difference in the RSS between two senders are fortunately big enough to allow capture effect at the maximum transmission power level. Extra signal strength from the M-BL increases the interference to the network as well as the signal strength at the intended receiver.

In general, PCBL always performs better at the distance (or at the locations) where the concurrent packet transmission does not cause interference on the other flow at the reduced signal strength level with PCBL while M-BL cause interference to the other communication. M-BL is only better when the interference under the PCBL scheme still causes strong interference each other and results in packet collisions while one sender could beat the other signal and successfully capture the channel with M-BL.

4.5.3 *Multi-hop, Multi-flow Experiments.* We performed multi-hop, multi-flow packet communication experiments in the 14 nodes testbed. Multi-hop reduces the throughput because intermediate nodes need to share the channel for both packet transmission and reception and multi-flow also reduces the throughput from the increased amount of data packets and interference. The testbed is divided into upper and lower sections and there are two senders and a receiver located in each section. Each section is separated with a dotted line in Figure 11 and two senders and a receiver are marked with S1, S2, and R respectively. We intentionally blacklist incoming packets from the other section to maintain two separate data flows one at each section. This is because we only want to evaluate the effect of interference in the multi-hop packet communication using either PCBL or M-BL.

Each sender continuously transmits a 230 byte packet at one second interval and the packet reception rates are measured at the receiver nodes. We use two-phase-pull directed diffusion routing protocols for a route-setup, and the actual data packet communication is enforced to be started after a successful communication route discovery. By doing this, the performance of the routing protocol is excluded from the comparison between the PCBL and M-BL.

Table IX shows the packet delivery rate (PDR) in our testbed experiment. Flow 1 means the upper section flows and flow 2 means the lower section flows. Each flow has two senders and a receiver as described earlier. When we compare the PDR between the cases with and without collision avoidance scheme, PCBL shows better performance without collision avoidance scheme while M-BL could deliver more packets when we enable collision avoidance scheme.

Reduced interference from the PCBL increases the probability of concurrent packet transmission in the wireless network and disabled collision avoidance scheme can reduce the number of packet communication with eliminated control packets. This is the reason why PCBL without a collision avoidance scheme can improve the packet delivery rate when the network is saturated with continuous multi-hop packet transmissions from multi-data sources like our experimental scenario. The extra transmission power used for M-BL causes stronger interference to more neighbor nodes and it drops the PDR and throughput of the network due to higher probability of packet collision without a collision avoidance scheme.

The comparison between PCBL and M-BL in our multi-hop experiment shows that both performs similar under the collision avoidance scheme (while the PCBL shows slight advantage) due to the limited bandwidth of the network from multi-hop and extra control packets. When we disable the collision avoidance scheme, PCBL delivers more packets benefiting more from the removed control packets by gaining more bandwidth for each node at lower interference level than M-BL.

4.5.4 *Lessons from the PCBL and M-BL comparison.* We now summarize the lessons learned from Section 4.5.1 to 4.5.3.

- **Benefits from PCBL:** *Reduction in transmission power consumption and interference.* PCBL improves the spatial reuse of the wireless channel and enables more simultaneous communications with less energy consumption.
- **Weakness of PCBL:** *Vulnerability to the dynamic environment change.* Environmental change can lead to the link quality change even though it is not severe compared to the case without transmission power control scheme. By setting the link quality control threshold outside of the range of link quality variation, we can avoid this problem and provide comparable performance with M-BL in providing consistent link quality.
- **Benefits from M-BL:** *Endurance to the minor interference and environmental change.* Extra transmission power (i.e., stronger than RSS_θ signal strength) ensures reliable communication under some environmental change or minor interference that is not prevented from the collision avoidance scheme.
- **Weakness of M-BL:** *Inefficiency in energy consumption and spatial reuse of the wireless channel.* Extra signal strength cause more interference to the network and the throughput of the network becomes lower as the interference strength

gets stronger.

The main advantage of M-BL is more consistent link quality when it has higher than RSS_θ signal strength at the receiver. For the PCBL, we can add some safeguard against environmental change and every link can provide consistent link quality by setting the RSS_θ even higher than the RSS_θ outside of the link quality variance range. PCBL can reduce (or even remove) the variance in the link quality under the environmental change with a little extra energy consumption.

5. CONCLUSION

In this paper, we have presented an experimental study of the effects of transmission power control on low-power wireless links. Our study identifies the causes of high variance in link quality under different environmental conditions and identified the transmission power range where the link quality dynamically changes (i.e., unreliable transmission power range).

The PCBL packet-based link quality control scheme is proposed to convert unreliable asymmetric and weak links to reliable wireless links which provide a consistent link quality. We incorporate a blacklisting approach together with our power control scheme to address the remaining unreliable link problem at adjusted transmission power level. The proposed transmission power control with blacklisting (PCBL) scheme provides energy-efficient link quality control with minimal channel interference, and provides a more stable and reliable network topology.

There are several directions in which this work could be extended. It would be helpful to verify our experimental observations on other radio platforms. We also hope to see our link quality control scheme used in a real application setting. PCBL can be potentially further enhanced if the power-control decisions were made by each node dynamically during network operation, taking into account interference from other active nodes in its neighborhood.

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