Experimental study of the effects of Transmission Power Control and Blacklisting in Wireless Sensor Networks

Dongjin Son[1,2], Bhaskar Krishnamachari[1,2] and John Heidemann[2]
{dongjins, bkrishna}@usc.edu, johnh@isi.edu
[1]Department of Electrical Engineering-Systems, [2]Information Sciences Institute
Viterbi School of Engineering, University of Southern California, Los Angeles, CA

Abstract— **We experimentally investigate the impact of variable transmission power on link quality, and propose variable power link quality control techniques to enhance the performance of data delivery in wireless sensor networks. This study extends the state of the art in two key respects: first, while there are a number of previous results on power control techniques for wireless ad hoc and sensor networks, to our knowledge nearly all of them have been simulation or analytical studies that assume idealized link conditions; second, while there are several recent experimental studies that have shown the prevalence of non-ideal unreliable communication links in sensor networks, these have not thoroughly investigated the impact of variable transmission power. We perform a systematic set of experiments to analyze how transmission power changes affect the quality of low power RF wireless links between nodes. These experiments show how significant variation in link qualities occur in real-world deployments and how these effects strongly influence the effectiveness of transmission power control. We then present a packet-based transmission power control mechanism that incorporates blacklisting to enhance link reliability while minimizing interference. The effectiveness of the proposed scheme is demonstrated via testbed experiments.**

Index Terms—**Transmission Power Control, Wireless Sensor Networks, Blacklisting**

I. INTRODUCTION

The instability and unpredictability of low power wireless channels due to fading and interference makes 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 [1,2,3]. 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 [4,5,6,7] 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.

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 [8,9,10,11,12,13,14,16,17,19,20,21,22]. However, to our knowledge, all 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.

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.

Based on our observations, we propose and evaluate a new transmission power control scheme. 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 realistic experiments that show reliable and

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energy efficient communication both in single and multiple flow scenarios.

Our experiments are performed on a PC104 testbed [23] with Mica2 motes. Directed Diffusion [24,25] routing and the S-MAC MAC protocol [26] in fully active mode [26] are used for our multi-hop experiments with transmission power control scheme. The Emstar [27] software platform and diffusion visualization tool [23] are used for protocol development and performance evaluation.

II. 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.

A. *Experimental Studies*

In [5], Ganesan *et al.* present a large scale (about 150 nodes) empirical study a mote-based sensor network; identifying the presence of weak links, link asymmetry etc., and studying their impact on the performance of simple flooding. Zhao and Govindan [4] 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. Lal *et al.* [7] study study the impact of link quality metrics such as RSSI and SNR on packet reception rates. The transitional region is observed also in [29] 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. De Couto *et al.* [30] introduce the ETX (expected number of transmissions) metric to improve the delivery performance of routing. None of these studies [4, 5, 7, 29, 30] primarily focus on link quality control using variable transmission power.

B. *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 [8,9,10,11,14,31] are primarily concerned about the energy-efficient network connectivity and the network lifetime issues.

Kubisch et al [8] proposed two distributed algorithms which ensures the network connectivity and increases the lifetime of the network. A topology control scheme based on the directional information is discussed in [9], where transmission power is increased until at least one neighbor node is found in each direction. Multiple routing daemons are used in CLUSTERPOW [31] 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 [10,11,14] to ensure connectivity while minimizing energy consumption.

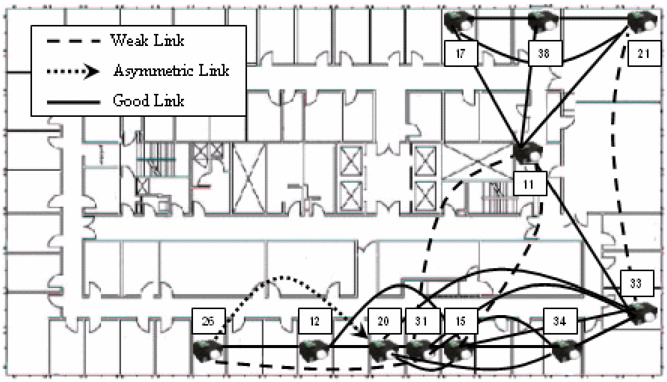


Fig. 1. PC104 Testbed at USC/ISI and a snapshot of weak, asymmetric, and good links

Researchers in [12,13,16,17,19,20,21] 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 [12] 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 [15,16,17]. 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 [18]. 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 [19,20,21].

Main differences between the related work 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).

III. COMMUNICATION LINKS IN WIRELESS SENSOR NETWORKS

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 varying several key parameters under different transmission power levels.

A. *The Effects of Unreliable Wireless Links*

Figure 1 shows the topology of the PC104 testbed [23] deployed and used for our experiments and contains the snapshot information of the link quality in packet reception rate (PRR) for every link in the testbed. We define two types of *unreliable links* with PRR metric. The communication link between two nodes is defined as a *weak link* when the qualities of the links in both directions are below the given PRR threshold value. The threshold value (TH_g) contains the minimum PRR requirement for a good link decision. The links with quality better than TH_g in only one direction are defined as *asymmetric links*. When we evaluate the qualities of the links based on the TH_g of 90%, five links are considered as unreliable links in our testbed (shown in figure 1): four weak links and one asymmetric link.

In our testbed, every pair of PC104 nodes are connected through a *good communication route* in which every link is classified as a *good link* (i.e., with higher than TH_g PRR in both directions). However, these five identified unreliable links are often 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 [24,25] routing protocol. The end-to-end packet delivery rates with single data flow (at the same experiment setting as IV-D) 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.

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.

B. The Effects of Transmission Power Control

The wireless link quality is closely related to the received signal strength and the transmission power control can be used to adjust the quality of the communication links to avoid asymmetric or weak links.

Pwr Link	0	1	2	4	6	8	10
11->31	54.3	86.3	**92.4**	100	100	100	100
31->11	0	27.2	83	85.7	**96.8**	100	100

Table. 1. Packet Reception Rate for the links between node 11 and node 31 at increased Transmission Power levels (dBm).

Table 1 shows the effect of transmission power increase on the quality of links between node 11 and 31. The transmission power values in the table represent the output powers of packet transmitters in dBm. Supported output power range for the transceiver [28] of mica2 motes ranges from -20 to 10 dBm. The PRR values in both directions are lower than TH_g value of 90% at default transmission power 0 dBm. The PRR of the $\mathrm{LINK}_{11\text{->}31}$ cross over TH_g at the transmission power 2 dBm and the PRR of the $\mathrm{LINK}_{31\text{->}11}$ exceeds TH_g at the transmission power 6 dBm. The symmetric and weak links can become good quality with transmission power control as the example shown in table 1.

Not only unreliable links can be converted to a good, reliable links with increased transmission power, new communication links can be discovered and used for packet delivery. Disconnected nodes in the sparse node area of the network and in the harsh communication environment might be able to build its connection back to the network at increased transmission power. The extra energy consumption of converting unreliable link to reliable link is often very small especially when the link quality is near the TH_g value at default transmission power and when the links are reactive to the transmission power change (*reactive links* are explained in D-6 of this section), and the benefits from the converted reliable links surpass the increased energy consumption. The experiment results in section IV-D present the benefits of converted, reliable wireless links with proposed transmission power control scheme and discuss the relationship between the link reliability and energy consumption.

When the transmission power control is involved in the link quality management, the meaning of asymmetric links and weak links should be redefined because the classifications made at default power may not be valid at other transmission powers. All of the five unreliable links identified in figure 1 are converted to good links at increased transmission power levels in our testbed measurements. Links are classified as asymmetric links only when they have asymmetric link qualities even with transmission power control, and the similar extended definition is used for the weak link.

Even though the amplified transmission power 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. Our transmission power control scheme is proposed considering these two side effects as well as the benefits of transmission power control.

C. Experiment Methodology

The link quality measurements in our testbed show varying link qualities for the 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).

Other than the results that show snapshot type information, the results represent mean PRR over multiple link quality measurements (5 times over ~120 packets) between PC104 nodes and the error bars show standard deviations of the means. Thirteen different transmission power levels ranged from -13 to 10 dBm are tested in indoor environments (figure 1): Between nodes placed either in the hallway or in office rooms. For some experiments, the link distance between the transmitter and receiver is varied between 9m to 26 m distance at 3m intervals, and only distances which show interesting results are presented in the paper.

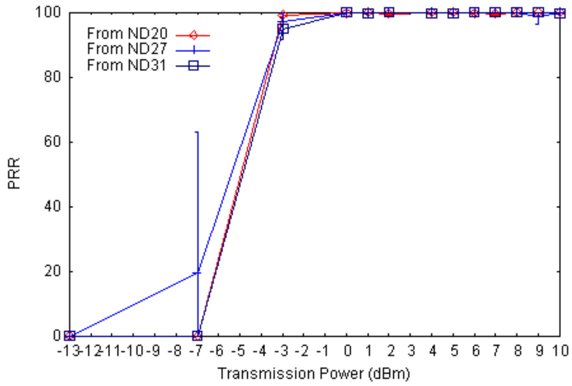


Fig. 2. Packet Reception Rate from different Transmitters to the same Receiver at 14 m distance.

D. *Experimental Study of Varying Transmission Power on a Single Wireless Link*

1) *Different Transmitters and a Same Receiver*

To see the effect of the difference in the hardware (i.e. sensor nodes) on the wireless link quality, we measure the link quality from three different transmitters to the same receiver in these experiments. The same kind of PC104 nodes are used with same software settings, and every transmitter sends packets from the exactly same location to the same static receiver. Link qualities from different transmitters are measured varying the transmission power and the distance between the transmitters and the receiver.

Performance difference from using different transmitters is not so obvious at close distance: no difference is recognized from the closer than 14m distance experiments. The difference between node 27 and the other two transmitters are observed from 17m distances and the difference between node 20 and node 31 appears from the experiment at 23m distance (figure 2 and 3).

From the experiment results, we can see that the inherent difference in sensor nodes (hardware variations) can cause a difference in the link quality, and this difference is more conspicuous in the low signal-to-noise ratio (SNR) situation. Obviously, there is no clear difference when the signal strength is too high at close distance or when that is too low at long distance. The PRR differences in transitional (or gray) area identified in prior studies [4,5,6] are related to this hardware calibration issue because this can be the factor that distinguishes link qualities at low SNR situation as figure 3 shows. The level of link quality difference is closely related to the transmission power level.

2) *Different Receivers and a Same Transmitter*

We also investigate the effects on the link quality when different nodes are placed as packet receivers. Exactly same positions are used for each pair of transmitter and receiver. Similar results as previous experiments are attained in these experiments: The link quality distinctions from using different receivers become obvious at long distance, 23m in our experiment (figure 4), while relatively minor or no differences are observed in other experiments at closer distance.

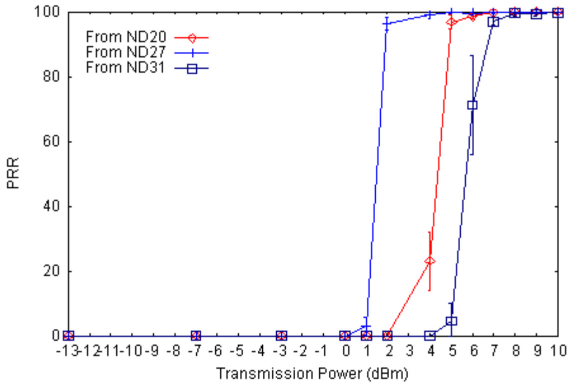


Fig. 3. Packet Reception Rate from different Transmitters to the same Receiver at 23 m distance.

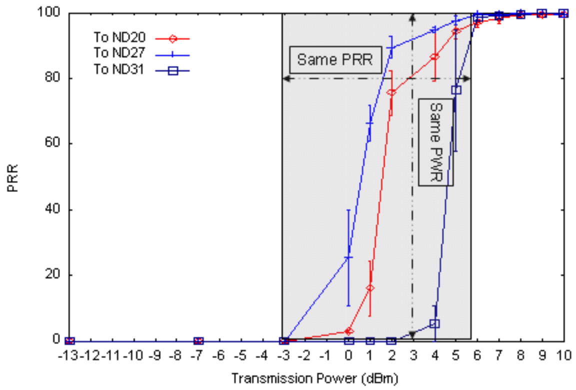


Fig. 4. Packet Reception Rate from the same Transmitter to different Receivers at 23 m distance.

The observed discrepancies in link qualities can be attributed to the different level of noise at the receiver and at the transmitter. When the experiment results at 23m are compared between the experiments with different transmitters and the experiments with different receivers (shown in figure 3 and 4), both experiments rank the link qualities of three involved nodes in the same order: node27, node 20, node 31. The inherent noise level at each node has a similar influence on the link quality when it is used as a transmitter and also as a receiver as these experiment results show.

In figure 4, the area in the transmission power range between -3 and 6 are shown in shade. The quality of each link is different at the same transmission power level (indicated with a vertical arrow) and the different transmission power is required for each link to reach the same PRR level (indicated with a horizontal arrow). The range of transmission power that generates this kind of variation is named as *unreliable transmission power range*.

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 to every node that is high enough for every link to be outside of the unreliable transmission power range. Second, by assigning a distinct transmission power for each link to provides the desired link quality level.

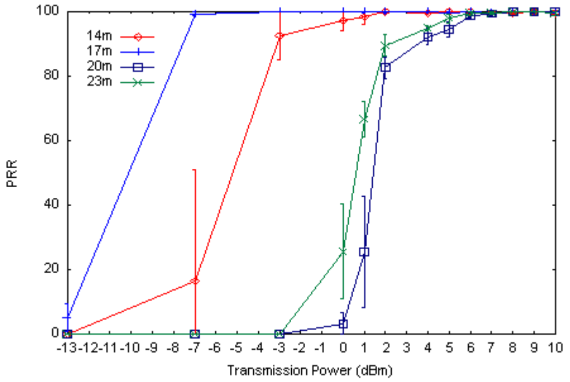


Fig. 5. Packet Reception Rate at different distance between node 34 (transmitter) and node 27 (receiver).

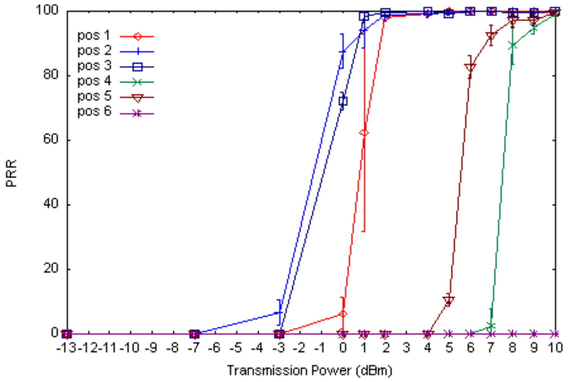


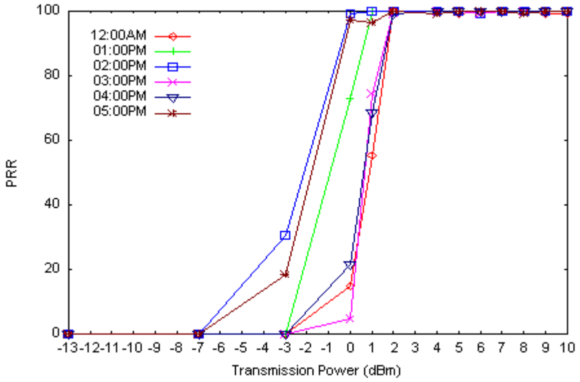
Fig. 6. Packet Reception Rates at five different receiver positions (pos 1-6) inside the same room at distance around 16m between node 12 (transmitter) and node 34 (receiver)

3) Wireless Link Distance (Path Loss)

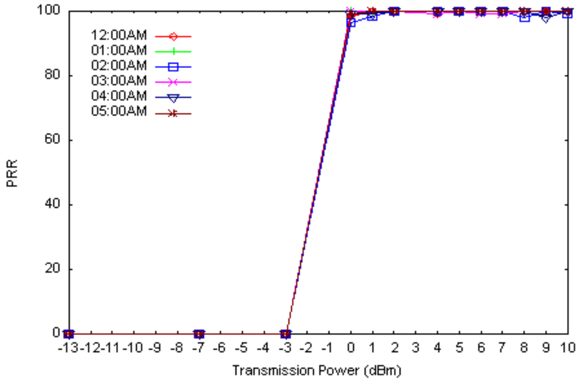
We present the effects of the wireless link distance and transmission power on the link quality in these experiments. Experiments are performed in the hallway of the building where a clear line of sight is available between the transmitter and receiver. As figure 5 shows, PRRs are different at different distances and at different transmission power levels. The order of link distance that shows better PRR at the same transmission power level is 17m, 14m, 23m, 20m. The effect of path-loss can be found at a relatively coarse granularity even thought the order is not linear to the link distance: closer distance (17m, 14m) has better link quality than longer distance (23m, 20m). The non-linear link quality order in our experiment results can be attributed to the severe indoor multi-path effect. Experiment results also show that new reliable, communication links that are not available at long distance at default transmission power (0 dBm) can be generated with transmission power control. Disconnected nodes (at default transmission power) in a sparsely deployed area and in harsh environments can build their connections to the network with transmission power control.

4) Node Location (Multi-Path & Interference)

To see the effects of different node positions, we measured link quality varying node locations at relatively long distance. In our experiments, both transmitter and receiver are located inside two offices located about 21m distance (there is no clear line of sight between the two nodes), and the receiver is repositioned as follows: on the desk (*pos1*), on the pc monitor (*pos2*), on the small table in the middle of the room (*pos3*), on the chair (*pos4*), under the desk (*pos5*), at the same coordinate of pos3 on the floor removing the table (*pos6*). Links to the positions on the floor and to the position on the chair where more signals are blocked by chair components show worse link qualities in general. All six positions are in the same office room and the link distance difference among these six positions are less than 2m, but the variation in the link quality is very significant with minor location change as shown in figure 6. We can realize from these results that (1) The multi-path and interference effects are severe in indoor where direct signal is weak (2) severe link quality variation can be expected with small movement of sensor nodes with low-power transceiver as well as small change in transmission power.



a) Daytime link quality change (in PRR) for the LINK$_{11\text{->}31}$



b) Nighttime link quality change (in PRR) for the LINK$_{11\text{->}31}$

Fig. 7. Packet Reception Rate variation comparison at different times

5) Time (Surrounding Environment Change)

The variations of link qualities are observed at different time from our link quality measurements in the testbed. Figure 7 shows five link quality snapshots of the same link (LINK$_{11\text{->}31}$) in the daytime and nighttime respectively. These clearly exhibit high variations in the link quality in the daytime while there is very minor difference in link quality among the five link quality measurements in the nighttime.

The changes in surrounding office environment during the daytime are the causes of this difference. The variation of link quality over time is also significant, but the difference in link quality is found only between the transmission power range -7

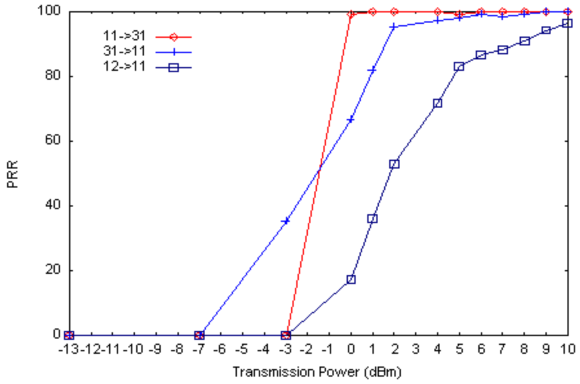


Fig. 8. Packet Reception Rate for three different links.

to 2 dBm (i.e., in the *unreliable transmission power range*). This means that $\mathrm{LINK}_{11\text{->}31}$ can be converted to a good link at transmission power level of 2 dBm or higher regardless of time change.

6) Reaction to the Transmission Power Change

From the experiments with different parameter settings varying transmission power level, different links or the same link at different setting shows different reaction to the transmission power change. Each link requires different amount of power increase to reach the same level of link quality. Some *reactive links* show very sharp change in PRR with small transmission power change, and other links show relatively slow change in link quality to transmission power change.

The link quality of *reactive links* can be controlled with small transmission power change and easily converted to a good link with small increase in transmission power. The link quality of this type of *reactive links*, however, shows high variation to the small environmental change at the same time. On the contrary, the links that show slow link quality change to the transmission power change exhibit reverse characteristics. They require more energy consumption to control their link qualities, but have less variation in link quality to the environmental change. However, the level of variation is only important within or near the unreliable transmission power range.

From the figure 8, we can identify asymmetrical reaction to the power change for the links between node 11 and 31. $\mathrm{LINK}_{11\text{->}31}$ is more reactive than the other direction and this difference can be the reason of asymmetric links within the unreliable transmission power range. Figure 8 also shows the different reactions to the transmission power change of different transmitters: $\mathrm{LINK}_{31\text{->}11}$ and $\mathrm{LINK}_{12\text{->}11}$

Each link requires different level of transmission power change to reach the same link quality and even the same link shows different level of reactivity for different level of link quality requirements.

IV. TRANSMISSION POWER CONTROL WITH BLACKLISTING

Based on the above experimental observations, we now develop a new power control mechanism.

A. Key Characteristics of Proposed Approach

We propose a transmission power control scheme with following characteristics.

(1) *Transmission power control for link quality control*: the primary purpose of transmission power control is to convert unreliable links (i.e., asymmetric and weak links) to reliable links.

(2) *Packet-based transmission power control*: a proper [1] transmission power is assigned to each packet based on the destination and type of the packet considering link quality requirement (i.e., link quality control threshold: $\mathrm{TH}_{\mathrm{LQ}}$).

(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 to reflect the diverse link qualities within the transmission range.

(4) *Blacklisting at adjusted transmission power level*: Not every link can be converted to a good link with transmission power control (i.e., even at maximum transmission power level) and new weak or asymmetric links can be generated at adjusted transmission power level. Blacklisting approach is combined together with transmission power control scheme to remove remaining unreliable links after the transmission power control. Both link-based and packet-based blacklisting schemes are discussed.

B. Algorithms

The basic steps of implementing our proposed transmission power control with blacklisting scheme (PCBL) are introduced. Two different approaches are introduced based on the transmission power and link quality optimization points.

1) PCBL algorithm (Optimization Prior to Routing)

Step 1) Collect Link Statistics in PRR metric

Each node measures the qualities of the links in PRR metric at different transmission power level (P_i : where i is the transmission power in dBm). PRRs at pre-selected transmission power levels (PRR_{P_i}) are collected.

Step 2) Select a Unicast Tx Power for each link

A *link quality control threshold* value in PRR (TH_{LQ}) is selected according to the required level of link reliability. An optimal transmission power for each link ($U_{i\text{->}j}$: unicast transmission power for the $\mathrm{LINK}_{i\text{->}j}$) is assigned with minimum transmission power that meets link quality requirement : $U_{i\text{->}j} = P$ where $\mathrm{PRR}_{P_i} > \mathrm{TH}_{\mathrm{LQ}}$ and $P = \min p_i$. Otherwise, $U_{i\text{->}j}$ is set to the maximum transmission power ($P_{\max}$).

Step 3) Blacklist *Unreliable links*

The links that cannot be converted to good links based on the *blacklist threshold* (TH_{BL}) are blacklisted and not used for any packet transmission or reception.

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[1] Proper transmission power means a setting that is as low power as possible while providing the desired PRR.

A *Link-based blacklisting*, which predefines network topology for every application, is applied in this step. However, a *packet-based blacklisting* is necessary for better utilization of the network when the requirements for the link qualities are not constant for different applications and for different type of packets. A *packet-based blacklisting* rather than a *link-based blacklisting* can be also used with adaptive TH_{BL} values.

TH_{LQ} is used to control the quality of each link and TH_{BL} ($<TH_{LQ}$) is employed to ensure the required reliability of the network. The gap between TH_{LQ} and TH_{BL} reduces the variation of the link availability and avoid frequent transmission power adjustments.

Step 4) Select a Broadcast Tx Power for each node

Broadcast transmission power of node i (B_i) is selected with the maximum unicast transmission power assigned in step 2: $B_i = \max U_{i\text{->}j}$: This make sure a node transmits broadcast packets with enough transmission power to reach every node with a good wireless link.

* To deal with dynamics, these steps can be repeated at pre-selected intervals

Our goal in transmission power control is to assign a close to optimal transmission power for each packet transmission and remove the negative effects of unreliable links. Proper transmission power setting can be identified for each link (unicast) and for each node (broadcast) based on the collected link statistics information at different power levels. Selected transmission powers satisfy the required link quality and also cause minimum interference to the network, New communication links that are not exposed at default transmission power level can be also discovered. The unreliable links that cannot be converted to good links with transmission power control and newly generated weak and asymmetric links from the new level of transmission power are prevented from the use with incorporated blacklisting scheme. The proposed algorithm is used to maintain required network link quality all the time (i.e., prior to any packet transmission).

A different transmission power control approach can be taken to reduce the overhead of collecting link statistics for some specific communication patterns. We can collect link statistics only for the nodes participating a packet delivery and converge to proper transmission power levels after a reliable routing path is found by a routing protocol (with small prior link statistics collection efforts) for long-lived communications.

2) On-demand Optimization for Long-lived Routing

Step 1) Collect Link Statistics only at the Maximum Transmission Power Level (P_{max})

Minimum link statistics to identify every available reliable links based on TH_{LQ} are collected at P_{max}.

Step 2) Blacklist Unreliable Links before using a Routing Protocol (*link-based blacklisting*)

This ensures routing protocols that use broadcast packets for route discovery construct a delivery path with only reliable links.

Step 3) Find a Delivery Path with a Routing Protocol

Step 4) Identify Unicast Transmission powers to use only for the Links in the Delivery Path

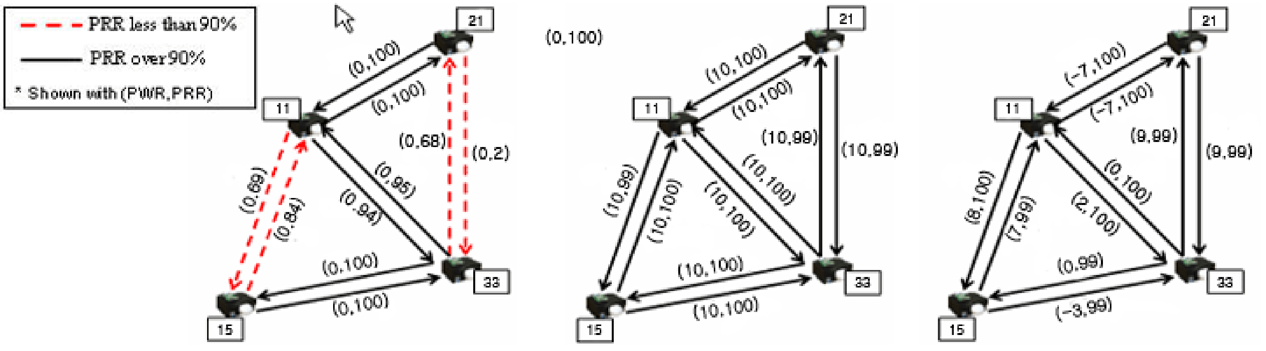
Link statistics for each transmission power level are collected between the nodes in the delivery path and close to optimal transmission power is selected for each packet transmission.

C. Optimization in Proposed Schemes

Optimized schemes to find an optimal transmission power and to adjust this value according to link quality changes can be developed based on the proposed algorithms. Other options include converging to an optimal transmission power based on the number of packet retransmissions and the RSSI (Received Signal Strength Information) change during the data delivery rather than based on the link statistics collection. We plan to develop and analyze such optimized algorithms and the trade-offs from the optimization in our future work.

The two proposed algorithms and the definition of unreliable links assume that the link user requires bi-directional links and use a *link-based blacklisting*. However, if the purpose of broadcast is to inform something to the network without any link level acknowledgement or future communication in reverse direction, asymmetric links can be utilized and weak links do not need to be blacklisted. Therefore, the meaning of *unreliable link* need to be interpreted differently for each communication purpose, and *packet-based blacklisting* rather than link-based is more appropriate in multi-purpose communication situations.

There are many parameter values that can affect the performance of transmission power control scheme: granularity of transmission power change, maximum transmission power (P_{max}), threshold values (TH_{LQ}, TH_{BL}), link statistics collection time interval. There are trade-offs for these parameter value selection. However, the link quality control threshold value (TH_{LQ}) is better to be set with a value outside the unreliable transmission power range to reduce the variation of link quality. (i.e., close to 100% PRR). A pure blacklisting approach without transmission power control scheme often use 80% or 90% PRR as a threshold value and it is not reasonable to use a higher threshold value. However, higher link quality can be achieved and therefore higher blacklisting threshold value can be used with transmission power control scheme.



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

Fig. 9. Topology change with different schemes. Each link shows (transmission power , PRR) pair information.

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

Table. 2. Standard deviations for the links with different levels of PRR .

As table 2 shows, the link with over 90% PRR still shows high variation in our seven day measurements in the testbed. It is because the value is still within the *unreliable transmission power range* where a small change can significantly affect the link quality. Fluctuation in link quality around the blacklist threshold value (TH_{BL}) may result in severe variation in the link availability that normally cause unnecessary packet drops. However, the links with close to 100% PRR, which show very minor variation, can be achieved with link quality control ability in PCBL. Reduced variation with transmission power control and the use of two different threshold values, for link quality control (TH_{LQ}) and blacklisting (TH_{BL}), prevent a hysterical effect in pure blacklisting approach and provide more reliable and stable links.

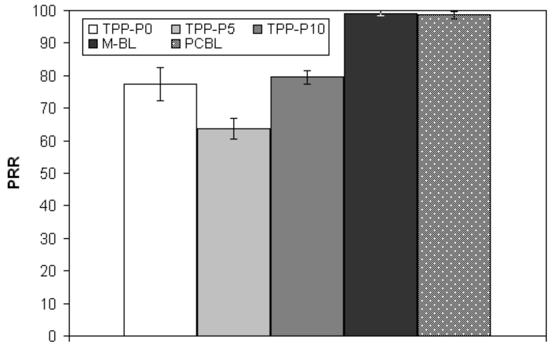


Fig. 10. Packet Delivery Rate from the experiments with five different schemes.

D. *Experiment Results (with Single Data Flow)*

The performance of proposed transmission power control with blacklisting scheme is evaluated in the 11 node pc104 testbed shown in figure 1. Even though we used relatively small, manageable number of nodes for our experiments, this testbed satisfies our experiment condition as it has a number of unreliable links. Larger and denser testbed experiments are expected to carry even more unreliable links and show further performance drop in packet delivery because 1) denser deployment may generate even more weak and asymmetric links and 2) larger testbeds increase the probability of having unreliable links in the delivery path.

Two nodes located farthest in the testbed are selected as a packet sender (node 21) and a receiver (node 26). Directed diffusion [24] is used as a routing protocol and fully active mode S-MAC [26] is used as a medium access control protocol. The following five schemes are compared in our experiments: (1) TPP-P0: Two Phase Pull diffusion at default transmission power 0 dBm (2) TPP-P5: TPP at increased transmission power 5 dBm (3) TPP-P10: TPP at increased transmission power 10 dBm (4) TPP with M-BL: TPP with Blacklisting alone at Maximum transmission power (10 dBm) and finally, (5) TPP with PCBL: TPP with our proposed transmission Power Control with Blacklisting. The experiment results show averaged end-to-end packet delivery rate (PDR) value over five ~1200 seconds experiments.

Figure 10 presents PDRs for five different schemes from the testbed experiments. The effects of increased default transmission power for every node are shown at transmission power 0, 5, 10 dBm. The PDR of TPP dropped at 5 dBm and also does not show much improvement at 10 dBm. The PDR in directed diffusion is highly dependent on how reliable delivery route is reinforced for packet delivery. Increasing the default transmission power for every node may solve some weak and asymmetric link problem and also useful to find a new route and save disconnected nodes. However, the increment in default transmission power is not a good way to increase PDR in most cases because (1) it cannot remove every unreliable link and may generate new lossy links, and (2) it uses up more network capacity at increased transmission power level.

Scheme	TPP-P0	TPP-P5	TPP-P10	M-BL	PCBL
PDR	77.5%	63.6%	79.5%	99.2%	98.7%

Table. 3. Packet Reception Rate for each scheme

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 generate the same network topology. Figure 9 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.

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. 4. The difference in energy consumption for packet transmission from our PCBL scheme

The amount of energy consumed for packet transmission in three different power control approaches are compared to see the effect of transmission power control on energy consumption[2] in table 4. Energy consumed for every broadcast packet (control packets from the directed diffusion) and unicast packet (data packets) transmissions are summed and compared against our PCBL scheme. Control packets used by MAC layer protocol (i.e., RTS, CTS, DATA, ACK) are excluded from the calculation.

In our testbed experiments with single data flow, M-BL scheme shows ~67% more current 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 default power of 0 dBm, consumes ~13% less energy than PCBL scheme.

Even though TPP-P0 scheme generates ~56% more unicast packets than PCBL on average, the energy saving in unicast packet is not significant due to several links with highly increased transmission power in our PCBL experiments. PCBL most likely transmits broadcast packets at higher transmission power than TPP-P0 and consumes more energy for broadcast packets. The ratio between unicast and broadcast packet (i.e., frequency of packet flooding) affects the performance of each scheme in energy consumption. When we compare energy consumption for each successful packet delivery, however, PCBL saves ~10.8% transmission power compared to TPP-P0. This proves the possible compensation from the increased network reliability that exceeds the extra energy consumed for some packet transmission.

E. Experiment Results (with Multiple Data Flows)

To see the effect of over-amplified transmission signal with blacklisting at maximized transmission power (M-BL) scheme, we performed experiments with multiple data flows. Three flows are involved in these experiments: Node 17 and 38 are sending packets to node 33 (flow 1&2) and Node 20 is sending packets to node 12 (flow 3) at 1 packet /sec send rate. The carrier sense sequence of RTS/CTS/DATA/ACK in S-MAC [26] prevents unicast packet collisions and the interference from different flows only cause a slight delay in packet delivery and does not affect end-to-end packet delivery rate (PDR) in low-traffic scenarios. When the communication links are saturated, the interference reduces the network capacity and causes packet drops from buffer overflows.

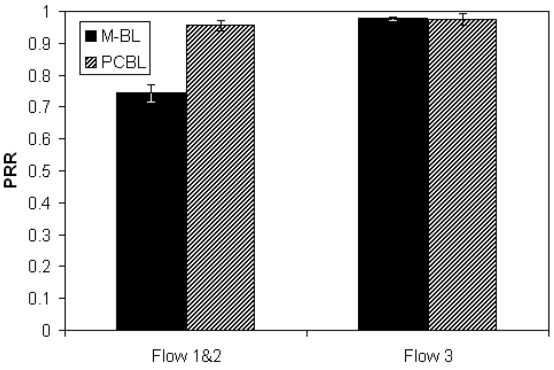


Fig. 11. Packet Delivery Rate from the experiments with three data flows

Figure 11 shows the PDR for flow 1&2 and flow 3 under different power-control schemes. 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.

Experiment results prove that over-amplified transmission power from M-BL uses up more network capacity with increased level of interference and deteriorates network throughput by saturating wireless channels. Thus, our proposed PCBL scheme shows better performance.

V. CONCLUSION AND FUTURE WORK

In this paper, we have presented an experimental study of the effects of transmission power control on the wireless link quality. The causes of high variance in link quality for each link and under different conditions are discussed and the transmission power range that is responsible for this divergence (i.e., *unreliable transmission power range*) is identified. Packet based link quality control scheme is proposed to convert unreliable asymmetric and weak links to reliable wireless links with consistent link quality. A blacklisting approach is incorporated together to handle remaining unreliable links at adjusted transmission power level and link-based and packet-based blacklisting approaches are introduced. The proposed transmission power control with blacklisting scheme provides energy-efficient link quality control with minimal channel interference, and generates new network topologies with more consistent and reliable wireless links.

Optimized ways to find an optimal transmission power level for each link and converge to new optimal transmission power

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[2] Calculation is based on the specification sheet in [28].

on link quality changes will be studied in our future work together with further details on related parameter value settings and related trade-offs.

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