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Distributed Transmission Power Control Algorithm for Wireless Sensor Networks*

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In this paper, we propose a distributed transmission power control algorithm which cannot only prolong the lifetime of sensor nodes by saving the energy consumption but enhance the performance of packet delivery ratio. Besides, it can also reduce the interference between transmitting nodes. Before designing our algorithm, we firstly investigate the impact of link quality when utilizing different transmission power by analyzing lots of experimental data, and then design our algorithm based on those experimental results. In our algorithm, each node utilizes the RSSI (Received Signal Strength Indicator) value and LQI (Link Quality Indicator) value of the radio to determine the appropriate transmission power for its neighbors. Our algorithm can dynamically adjust the transmission power with the environment change. All of our experiments are implemented on the MICAz platform. The experimental results show that our algorithm can save power energy and guarantee a good link quality for each pair of communications.

Keywords: energy consumption, power control, power saving, wireless networks, sensor networks

1. INTRODUCTION

Power saving is one of the most important issues in wireless sensor networks (WSNs). Researches with regarding to solve power saving problems in WSNs can be classified into two major categories according as the way they focus on. One is media access control (MAC) layer solution [1, 9-12, 15, 17] and the other is network layer solution [2-4, 7, 8, 14]. In MAC layer solution, most of researches use the scheduling method to make nodes wake-up or sleep periodically. Node's scheduling usually needs global time synchronization and some problems such as clock drift should be solved when implements time synchronization on sensor nodes. In contrast to MAC layer solution, the network layer solution utilizes adjusting proper transmission power to achieve power saving.

The benefits of adjusting transmission power control allows several improvements in the operation of WSNs such as establishment of links with high reliability, communication with the minimum energy cost, and better reuse of the medium. We describe those advantages in detail. First, power control technique can be used to improve the reliability of a link. Since nodes upon detecting links reliability is below a required threshold, they

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will increase the transmission power in order to lower the probability of receiving corrupted data. Second, the nodes which communicate at a fixed transmission power will waste more energy since some links already have a high probability of successful delivery. Consequently, the transmission power control algorithm could help to decrease the transmission power to a proper level which guarantees link quality is still high but energy consumption is low. Third, nodes usually communicate at the exact transmission power that will not cause large transmission range to interfere with other's communication. Thus, nodes decrease the amount of collisions in the network. Those reduced collisions will enhance network utilization, lower latency time and also reduce the retransmission.

According to our experiments if we use the static transmission power, the link quality usually interfered by background noise. This will cause the loss of the packets and then decrease the packet delivery ratio. In this way, we want to adjust the transmission power to adaptive the environment change and keep the better packet delivery ratio. The solutions in the MAC layer do not provide a way to guarantee the packet delivery ratio and set the proper transmission power. Accordingly, we use the concept, adjusting transmission power, in network layer solutions to design our algorithm. However, how to find proper transmission power which varies with time or other affecting factors for each sensor node is a difficult problem. Too low transmission power maybe easily results in the existence of broken link between two nodes. On the contrary, utilizing excessively high transmission power is inefficient because it may cause the mutual interference in the shared medium and consume large of limited battery energy. Therefore, we design an algorithm to dynamically adjust a proper transmission power for each sensor node based on our large number of experimental results.

In order to propose our algorithm, we design a series of experiments to collect the data of three parameters, RSSI (Received Signal Strength Indicator), LQI (Link Quality Indicator) and packet delivery ratio, on transmitting data with different transmission power which vary with the distance between two sensor nodes. Next, we analyzed previous experimental results to find out the relations between the three parameters and transmission power. Our contribution in this paper is twofold. One is we provided a thorough experimental study of how low-power wireless links behave with respect to variable transmission power, RSSI and LQI. And through those experimental results we design a transmission power control algorithm to adjust the proper transmission power for each pair of communication nodes. The other contribution is we implement the transmission power control algorithm on our implemented testbed platform which is compatible to MICAz to verify its performance.

The rest of this paper is organized as follows. Section 2 reviews related work. We present our distributed transmission power control algorithm in section 3. Section 4 evaluates the performance of our algorithms through realistic experiments. Concluding remarks are made in section 5.

2. RELATED WORK

Two categories of literatures are related to our research. One is to investigate the characteristic of wireless links in sensor networks through analyzing several experimental data. The other is considering how to achieve controlling transmission power in

WSNs. Here are some researches [5, 6, 15, 16, 18] related to the first category. In [16], the authors have done several experiments and analyzed the relationship between the RSSI value and LQI value with packet delivery ratio. Because the fluctuation of LQI value is much more than the RSSI value within a period of time detected by a sensor, the authors presented a method to predict the packet delivery ratio by collecting the numbers of LQI value. They found that average these LQI value in different average window size will affect the accuracy of prediction of the packet delivery ratio. Average window size is the average LQI value of several numbers of packets. Therefore, the more average window size will result in higher accuracy of prediction. The authors in [5] presented one kind of cost metric named as “link inefficiency” to measure the energy cost of links. The link inefficiency is the inverse of the packet delivery ratio. Note that, a perfectly efficient link has link inefficiency 1. The link inefficiency grows as a link get worse. In other word, the inefficiency increases corresponding to a larger amount of energy spent on that link due to retransmissions. In this concept, they also proposed a mathematical way to predict the relation between the signal to noise value and the packet delivery ratio, beside they also provide a measuring way with the energy cost on the link.

Some researches [16, 19] have revealed the existence of three distinct reception regions in a wireless link. Those reception regions are disconnected region, transitional region, and connected region. These three reception regions correspond to three kinds of link status when the link’s transmission power is from minimum to maximum. Disconnected region means the packet delivery ratio is zero. On the contrary, connected region means the packet delivery ratio is almost 100%. The transitional region between the disconnected and connected regions is often quite significant in size and generally characterized by high-variance in reception rates and asymmetric connectivity. Furthermore, the authors in [15] are also systematically investigated the affection of concurrent transmission in the transitional region through experiments. And it also discusses the effect of multiple interferers in the transitional region. The authors in [6] presented an accurate prediction model in power consumption on sensor node based on the execution of real application and OS code experiment. It can also predict the life time on sensor node.

On the other hand, some research efforts in [2-4, 7, 8, 14] have been carried out on controlling transmission power. The authors in [3, 4] proposed a protocol to determine the proper transmission power for each sensor node to connect a specific number of neighboring nodes. This specific number is a threshold value which is used to determine the required transmission power for sensors. If the number of neighbors of a node is above the threshold value, it will decrease the transmission power. On the contrary, if it below the threshold value, a node will increase the transmission power. The main purpose of keeping the specific number of neighboring nodes is the node can cost less energy on maintaining links to neighboring nodes such that the network is connected and prolongs the network lifetime.

The authors in [2] presented two methods to calculate the ideal transmission power. The first one is through node interaction including two phases. In the first phase, the transceiver sent the probe query message to the receiver. After the receiver received the probe query message, it will send ACK message back to the transceiver. In this way, the transceiver will check whether the receiver is received the probe query message through ACK message. Then the transceiver will determine to increase or decrease the transmission power. Next, the transceiver continuously sends the probe query message to the receiver until it cannot receive the ACK message. The transmission power which transceiver used at this time will become the initial transmission power for the receiver, and then it will get into the second phase. In second phase, the node always dynamically changes its transmission power depending on a number of confirmed ACKs of consecutive transmissions. If the number of consecutively received ACKs is over a predefined threshold value, the transceiver will decrease the ideal transmission power with one level. Correspondingly, if the numbers below the other predefined threshold value, the transceiver will increase the transmission power with one level. The second method of this literature is using the ratio of "signal attenuation". The ideal transmission power can also be calculated as a function of signal attenuation. The receiver will tell the transceiver what the signal strength it received. And then the transceiver will adjust the transmission power to make the receiver having the proper signal strength through the calculated function.

The authors in [14] used the packet delivery ratio to determine the proper transmission power. It divided the transmission power into seven discrete transmission powers. The nodes broadcast some packets to their neighboring nodes using 7 different transmission powers and let them to collect packets and calculate the packet delivery ratio. Each neighboring node chooses the minimum transmission power which packet delivery ratio is above the required threshold as a proper transmission power. Furthermore, the authors also present the concept of blacklist. Every node maintains its own blacklist which is a list recorded its neighboring node's ID that the node does not want to transmit packets to them. The authors in [7] have done several experiments and find out that the least RSSI for guaranteeing good packet delivery ratio is at least above – 92dBm. And then they use the linear programming method to predict the accurate transmission power by collecting packets within a period of time of communicating with neighboring nodes. The equation produced by the liner programming which is used to find the mapping relation between the transmission power (at the sender) and the RSSI value (at the receiver). When the node communicated with the neighboring node, the sender will choose the RSSI value in equation which above the picked RSSI threshold (– 92dBm) to map the transmission power in the equation. In other word, it guarantees the good packet delivery ratio.

In this paper, our approach is composed of previous two main schemes in network layer to design our algorithm, and we also implement our protocol on real sensor nodes.

3. DISTRIBUTED ADAPTIVE TRANSMISSION POWER CONTROL ALGORITHM

Our power control algorithm is based on the RSSI value and LQI value of the received packets. Before designing our algorithm, we have some experiments to understand the attributes of real sensors. The following experiments are executed on MICAz platform. The RF module of MICAz is Chipcon CC2420 [20] which is used to manage the transmission and reception of wireless signal. The maximum transmission range is able to reach about 100 meters. Besides, the energy cost on the largest transmission power (0dBm) setting will cost 17.4mA, and the smallest transmission power (– 25dBm) setting will cost 8.5mA. In MICAz, the RSSI value can be got from the registers of CC2420 chip.

Beside the RSSI value, the CC2420 chip provides an average correlation value for each incoming packet called LQI value. This unsigned 8-bit value can be looked upon as a measurement of the "chip error rate." According to our experiments, LQI and RSSI value have a very high correlation. The LQI value is not only the indicator of quality of a received packet but also an indicator of the received signal strength. The MICAz supports 32 power levels setting for data transmission [20]. We do not need so many levels in our experiments due to the environment is always changing from time to time. If we use 32 levels of transmission power, it will cause our algorithm to frequently changing its transmission power level. That is a little environment change will easily cause the change of transmission power. In this way, we divide the 32 original transmission power levels into 8 power levels. Every interval between our defined power levels is corresponding to 4 original CC2420's transmission power levels.

In our algorithm, we will utilize both RSSI and LQI value as a basis of adjusting transmission power level. The keyword "transmission power level" in the following article means our defined 8 transmission power levels. Our algorithm consists of initial phase and maintaining phase. In initial phase, each node tries to find a proper transmission power level for its neighboring nodes. In maintaining phase, each node will dynamically adjust a proper transmission power level according to the average RSSI and LQI value of the received packets.

3.1 Initial Phase

In initial phase, each node determines a proper transmission power level for each of neighboring nodes. Firstly, each node broadcasts 800 probing packets (*PL_probe*) with transmission power level from high (level 8) to low (level 1) in turn. That is, each node will broadcast 100 packets for each transmission power level. The *PL_probe* packet includes two fields. One is ID field which is used to tell the received node about the source ID of the packet. The other one is power level field which indicates the transmission power level of the packet. Before sending a packet, the sensor node will count down a default system back-off time. The range of the default system back-off time is 1 to 16 time slots and each time slot is 0.32ms. According to our experiments, there exists heavy collision on communications if the node density is higher than ten nodes within a hop. In order to increase the packet delivery ratio, we design a new back-off time including two random time slots. One is user back-off time slots (T_u) which is a back-off time randomly generated between 1 to R_u time slots and each time slot is one millisecond. The other one is system back-off time slots (T_m) which is a back-off time randomly generated between 1 to R_m time slots and each time slot is 0.32ms. Thus, the total back-off time for a node is summation of T_u and T_m.

When a node starts to send a *PL_probe* packet, it needs to generate two random time slots T_u and T_m, respectively. Here, we give experiments to decide the proper value of R_u and R_m. In our experiments, we utilize 10 MICAzs which are all located in one hop distance. The distance between each pair of nodes is about one meter. Each node randomly generates T_u and T_m and broadcasts 100 *PL_probe* packets in maximal transmission power level. If a node receives a broadcast packet during counting its back-off time, it will stop counting and regenerate T_u and T_m again. After waiting the total back-off time T_u plus T_m, a node will broadcast its probe packet. Under various values of R_u and R_m, the

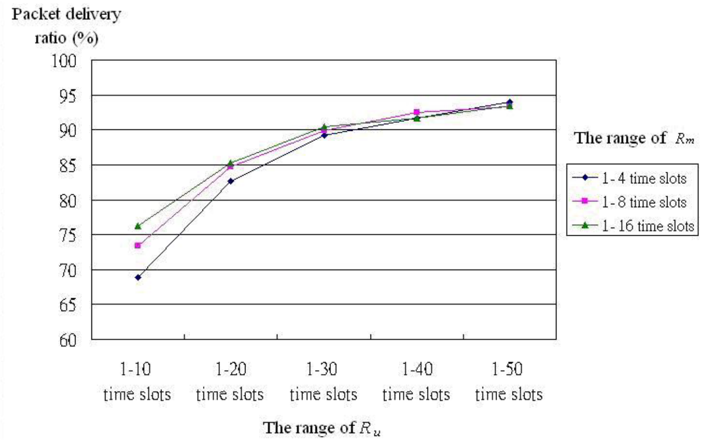


Fig. 1. The packet delivery ratio with various ranges of R_u and R_m.

packet delivery ratio is shown in Fig. 1. Each experiment is repeated five times. Obviously, the packet delivery ratio increases as R_u and R_m increase. However, the larger values of R_u and R_m will cause longer delay time to complete the initial phase. Therefore, the values of R_u and R_m are set as 30 and 8, respectively in our algorithm and the packet delivery ratio is about 90%.

Secondly, once a node receives the *PL_probe* packets from its neighboring nodes, it will count the number of packets received from each neighboring node with each power level. Each node can determine a minimum transmission power level for each of its neighboring nodes according to if the number of packets received for the minimum transmission power level is larger than a threshold. Since each node broadcasts 100 *PL_probe* packets for each transmission power level and the packet delivery ratio is about 90%, the threshold is set as 80. Therefore, if a node *A* can receive more than 80 packets from a node *B* with a minimum power level *k*, the power level *k* becomes the initial transmission power level from node *B* to node *A*. However, if the number of received packets from a node is less than 80 for all of its transmission power levels, the initial transmission power level for the node is set to maximum power level (level 8). Here, we adopt the packet delivery ratio 80% as the threshold instead of RSSI value for determining the initial transmission power level. This is because the RSSI value usually had to be collected for a period of time; however, we want to reduce the executing time of the initial phase as much as possible. Besides, in the initial phase every node broadcasts *PL_probe* packets in a short time that will cause interference and let each node collected inaccurate RSSI values.

When a node broadcasts all the *PL_probe* packets, it can find the initial transmission power level for each of its neighboring nodes. Then each node will broadcast an *Initial_Power_Level* packet including the initial transmission power level of its neighboring nodes. In order to avoid packet collision, the *Initial_Power_Level* packet is broadcasted 10 times. When a node received the *Initial_Power_Level* packets from its neighboring nodes, it will enter the maintaining phase. The following is our initial phase algorithm.

Algorithm 1 Initial Phase

Step 1: Each node broadcasts 800 *PL_probe* packets from power level 8 to power 1 circularly.

Step 2: Each node determines the initial transmission power level for each of its neighboring nodes according to the received *PL_probe* packets. The initial transmission power level is the minimum power level whose number of packets received is larger than 80.

Step 3: Each node broadcasts a packet including the initial transmission power level for each of its neighboring nodes. The packet is broadcast 10 times repeatedly.

Step 4: Each node receives the initial transmission power level from its neighboring nodes and enter to maintaining phase.

3.2 Maintaining Phase

The main purpose of the maintaining phase is adaptively determining and adjusting the proper transmission power level with environmental change. Each sensor node utilizes the collected RSSI value and LQI value to determine the proper transmission power level that can achieve high packet delivery ratio and save transmission energy. We firstly describe the algorithm of maintaining phase and then explain how to find out the arguments used in the maintaining phase through some experiments.

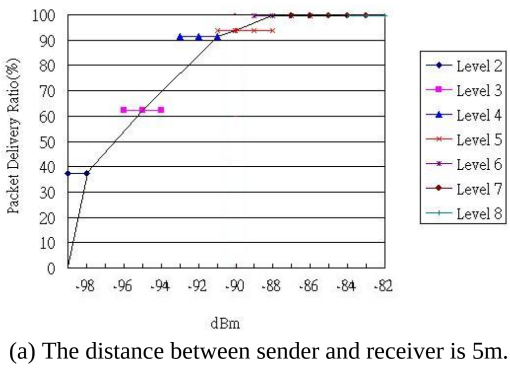
Firstly, in order to reduce the control overhead and save transmission energy, each node will choose at most five nodes as its neighbors. If the number of neighbors is larger than five, the nodes which have less initial transmission power levels than other nodes are selected as neighbors. Secondly, each node attaches the used transmission power level when forwards or transmits data packets to one of its neighboring nodes. Once a node receives a data packet, it will send an ACK packet back to the sender. The ACK packet piggybacks the RSSI and LQI values that capture from its CC2420 chip's registers when received the data packet. Each node can collect the received RSSI value and LQI value from its neighboring nodes. After each sensor node collects a number of RSSI and LQI values, the node will determine a new transmission power level for each of neighbor nodes accordingly. The numbers of RSSI and LQI values will be determined in experiments.

Here, we will describe how a transmission power level is determined according to the received RSSI and LQI values. When a node *A* received a number of RSSI and LQI values from one of its neighbors *B*, node *A* averages the RSSI values and LQI values which are denoted *AvgRSSI* and *AvgLQI*, respectively. If the *AvgRSSI* is larger than a threshold R_H ($R_H < AvgRSSI$), node *A* will decrease the transmission power level by one for node *B*. If the *AvgRSSI* is smaller than a threshold R_L ($AvgRSSI < R_L$), node *A* will increase the transmission power level by one for node *B*. If the *AvgRSSI* is between the RSSI thresholds R_L and R_H ($R_L \leq AvgRSSI \leq R_H$) and *AvgLQI* is smaller than a threshold L_{TH} ($AvgLQI < L_{TH}$), node *A* will increase one transmission power level for node *B*. This is because the link quality is not good enough and the signal strength may become weak or break later. In the rest conditions, node *A* will keep the same transmission power level for node *B*.

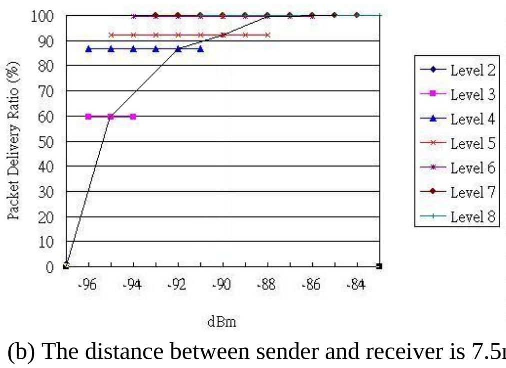
Since the large variation of signal interference or sudden increase of background noise, it is possible we cannot receive a packet with a reduced transmission power level in a moment. Therefore, in order to decrease the transmission delay, if a sending node cannot receive an ACK packet from receiver after waiting a period time, the node will use the maximum transmission power level to retransmit the data packet immediately. According to our experiments, the signal interference from node *A* to node *B* is different from node *B* to node *A*. However, in most of time the difference of their transmission power levels is less than three levels in indoor environment. Therefore, when a node *A* find its transmission power level to node *B* is lower than three levels compared to the transmission power level from node *B* to node *A*, node *A* will increase its transmission power level such that their difference is equal to three levels. In addition, when a node *A* receives a packet from a node *B* whose transmission power level is smaller than one of its currently maintaining nodes, node *A* will use node *B* to replace the node which has larger transmission power level than node *B*.

In the following, we do the experiments to determine the arguments of R_L, R_H, and L_{TH}. In the first experiment, we use two MICAzs, one is as the sender and the other one is as the receiver. In order to promote the experimental accuracy, we experiment in several environments of indoor corridors. The distances between the sender and receiver are 2.5m, 5m, 7.5m, 10m, 12.5m, and 15m, respectively. For each transmission distance, the sender transmits 8000 data packet with power level from high (level 8) to low (level 1) in turn and the transmission interval is 100ms. Each experiment is the average of seven rounds. The receiver separately counts the number of received packets and captures the RSSI value in each transmission power level and distance. In our experiments, if the RSSI value is larger than − 90dBm, the packet deliver ratio will larger than 90% in most of cases. Since we have huge amount of experimental data and the experimental results are similar, we only choose two representative results for illustration as shown in Fig. 2.

In Fig. 2, each bar line represents the range of collected RSSI values. For example, in Fig. 2 (a) the level 4 bar line represents that the range of RSSI values of received packets is between − 93dBm and − 91dBm. In Fig. 2, we use a curve as a trend line and it passes through the bar line of each transmission power level. The intersection point of the curve line and a bar line represents the most number of received RSSI values on that transmission power level. For example, in Fig. 2 (b) the RSSI value of most of received packets is − 92dBm for power level 4. We conclude the experimental results that if the



(a) The distance between sender and receiver is 5m.



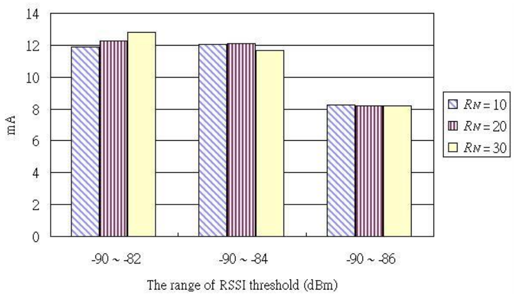
(b) The distance between sender and receiver is 7.5m.

Fig. 2. The RSSI value and packet delivery ratio in different transmission power and distances in corridor.

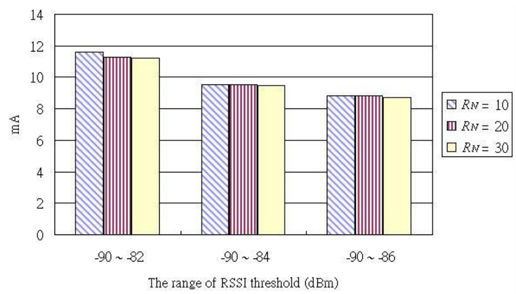
received RSSI value is larger than or equal to – 90dBm, the packet delivery ratio will above 90% no matter what the distance between the nodes. Therefore, the R_L is set as – 90dBm in our protocol.

After we get the R_L from the previous experiment, we design an experiment to determine the RSSI threshold R_H. In this experiment, the distance between two MICAzs is 5 meters. The sender sends data packets for 10000 seconds and the transmission intervals are 100ms, 1s and 10s, separately. In order to determine the R_H, we experiment three pairs of RSSI ranges (– 90dBm, – 86dBm), (– 90dBm, – 84dBm), and (– 90dBm, – 82dBm). The sender will accumulate the RSSI values from ACK packets and averages the accumulated RSSI values per 10, 20 and 30 packets to get the *AvgRSSI*. Let R_N denotes the number of packets used to get the *AvgRSSI*. We also calculate the energy cost for this experiment. We take five experimental results to average for each range of RSSI threshold. The experiment results are shown in Figs. 3, 4, and 5.

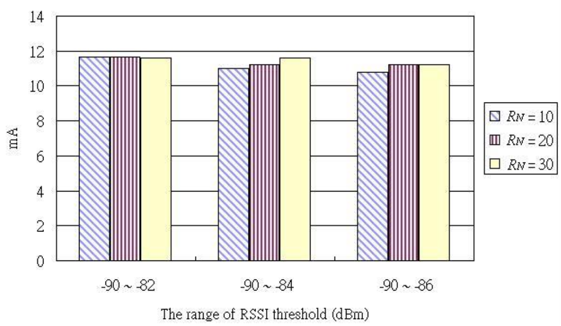
In Fig. 3, if the range of RSSI threshold is wider, the sender has more opportunity to use high transmission power level since the *AvgRSSI* is easily located between R_L and R_H. In this way, the sender often has no chance to decrease its transmission power level. In Fig. 3, the range of RSSI threshold from – 90dBm to – 86dBm has the minimum energy cost per packet compared to other two ranges in various transmitting interval (100ms, 1s and 10s) and threshold R_N (10, 20 and 30). In Fig. 4, the wider range of RSSI threshold has higher packet delivery ratio. However, their difference is small. Therefore, the R_H is set as – 86dBm. After determining the range of RSSI thresholds, we want to determine the R_N. In Fig. 4, we can find that the best R_N is 30 for small packet transmission interval



(a) The transmitting interval is 0.1s.

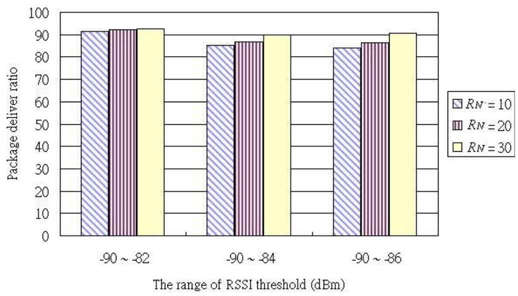


(b) The transmitting interval is 1s.

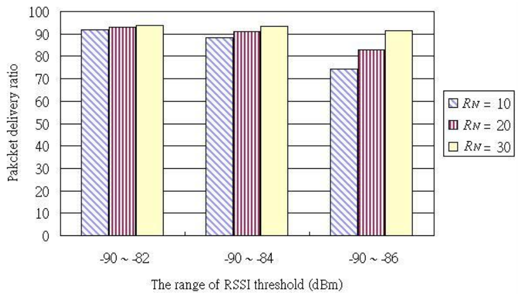


(c) The transmitting interval is 10s.

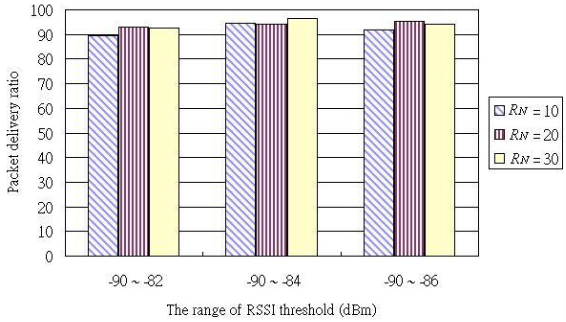
Fig. 3. Energy cost per packet with different range of RSSI threshold and R_N.



(a) The transmitting interval is 0.1s.

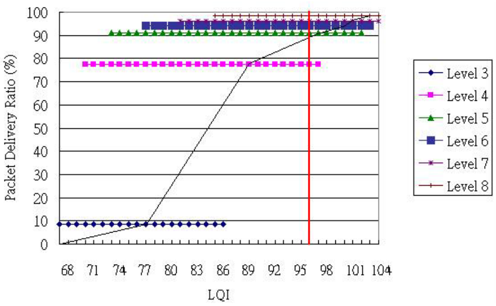


(b) The transmitting interval is 1s.

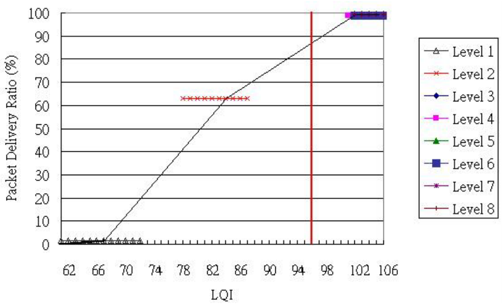


(c) The transmitting interval is 10s.

Fig. 4. Packet delivery ratios with different ranges of RSSI threshold and R_N.



(a) The distance between the sender and the receiver is 7.5m.



(b) The distance between the sender and the receiver is 5m.

Fig. 5. The LQI value and packet delivery ratio in different transmission power levels.

and large transmission interval. This is because the larger R_N can get more stable *AvgRSSI* than others whatever in different range of RSSI threshold. Because the environment is change from time to time, the large R_N can absorb the unusual RSSI value in order to get stable *AvgRSSI* value. Therefore, the R_N is set as 30 in our protocol.

In the following experiments, we show how to find out the LQI threshold (L_{TH}) such that the packet delivery ratio will not less than 90%. The simulation environments are same as the experiment in Fig. 2. In Fig. 5, we use the curve (black line) as the trend line and it passes through the bar line of each transmission power level. The intersection point between the curve and each bar line represents the most number of LQI values which are captured on that transmission power level. We can see that the background noise and signal interference in Fig. 5 (a) are more serious than in Fig. 5 (b). This is because that the distribution of LQI value in each transmission power level in Fig. 5 (a) is wider than the same transmission power level in Fig. 5 (b). So the distribution of LQI value in each transmission power level can indicate the background noise of current environment. Besides, we can see when the *AvgLQI* is larger than or equal to 96, the packet delivery ratio will above 90%. So we set L_{TH} as 96 in our protocol. The vertical line in Fig. 5 is equal to 96.

Let L_N denotes the number of packets used to get the *AvgLQI*. In the following experiment, the range of RSSI threshold is from − 90dBm to − 86dBm and R_N is 30. The authors in [16] presented that the distributed range of received LQI value usually wider than the received RSSI value especially when the link quality is bad. Therefore, we experiment four different L_N values 30, 60, 90, and 120 with four different packet transmitting intervals 100ms, 1s, 10s, and 100s. The sender follows our proposed scheme of maintaining phase to adjust the transmission power level based on different L_N values and packet transmitting intervals. In Fig. 6, the higher L_N is, the higher packet delivery ratio is. In Fig. 7, there is only a little difference in the average energy cost per packet for different L_N under a fixed transmission interval. Thus L_N is set as 120.

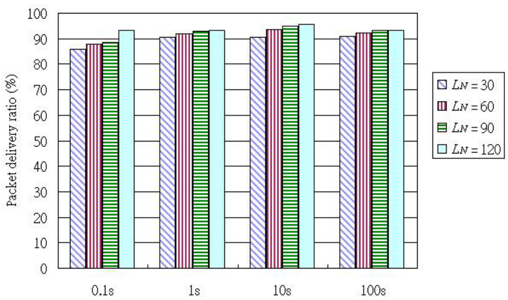


Fig. 6. Packet delivery ratio with different packet transmitting interval and L_N value.

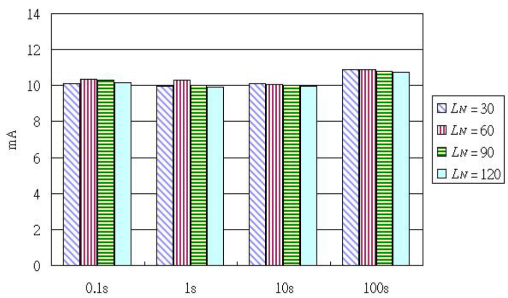


Fig. 7. Average energy cost per packet with different packet transmitting interval and L_N value.

We summary our algorithm of maintaining phase as follows.

Algorithm 2 Maintaining Phase

***PL*:** The current transmission power level.

Step 1: Each node chooses at most five nodes as its neighbors.

Step 2: When a node receives a data packet from a sending node, the node sends an ACK packet piggybacks the RSSI and LQI values to the sending node. If a node finds its transmission power level is lower than three levels corresponding to one of its neighbors, the node will increase its transmission power level such that their difference is equal to three levels. When a node detects a new node which the transmission power level is smaller than one of its neighboring nodes, the new node will be used to replace the neighboring node.

Step 3: Each node will calculate *AvgRSSI* for every 30 ACK packets received and *AvgLQI* for every 120 ACK packets received. If a node cannot receive an ACK packet from receiver after waiting a period time, the node will use the maximum transmission power level to retransmit the data packet.

Step 4: When a node receives 30 ACK packets from one of its neighbors, the node will adjust the transmission power level for the neighbor with the following rules.

$PL = PL + 1$ when $AvgRSSI < -90$dBm.

$PL = PL + 1$ when $-90\text{dBm} \le AvgRSSI \le -86$dBm, and $AvgLQI < 96$.

$PL = PL$ when $-90\text{dBm} \le AvgRSSI \le -86$dBm, and $96 \le AvgLQI$.

$PL = PL - 1$ when $-86\text{dBm} < AvgRSSI$.

4. EXPERIMENTAL RESULTS

In this section, we investigate the performance of our Distributed Transmission Power Control (DTPC) algorithm on our implemented testbed platform. Our testbed platform consists of 17 wireless sensor nodes which are compatible with MICAz and deployed on the indoor ceiling as illustrated in Fig. 8. We experiment three different routing paths that are routing path 1 (16 → 17 → 15 → 10 → 9 → 8 → 7 → 6 → 13 → 2 → 3 → 4), routing path 2 (4 → 3 → 2 → 13 → 6 → 7 → 8 → 9 → 10 → 15 → 17 → 16) and routing path 3 (16 → 17 → 15 → 14 → 13 → 12 → 11 → 1 → 3 → 5) as shown in Fig. 8. The source node of each routing path transmits a packet to the destination node in every 10 seconds. In each routing path, we individually experiment for 24 hours in order to get long term experimental results. We compare the performance of DTPC with the nodes always send packets in the Always Maximum Transmission Power (AMTP) level. In order to observe the effect of two mutually reverse routing paths on packet delivery ratio and energy consumption, we let the direction of routing path 2 is reverse of routing path 1. Unlike routing paths 1 and 2 pass through some obstacles such as walls and metal doors, the routing path 3 passes though the corridor environment to experiment the performance of different environments.

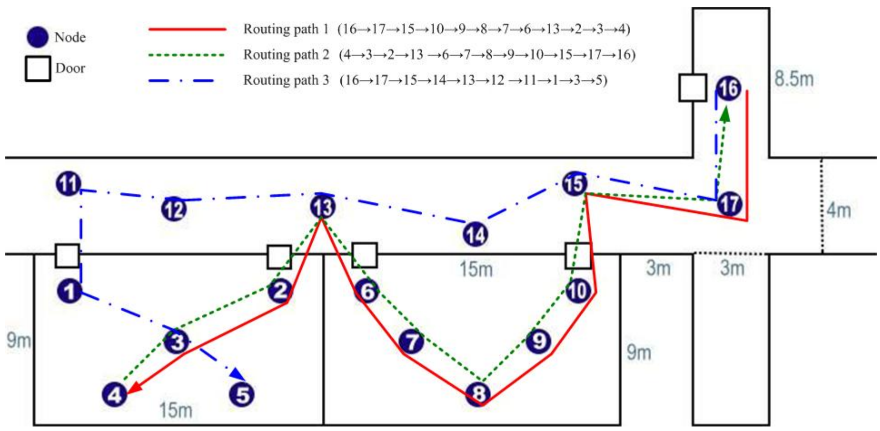


Fig. 8. The illustration of our test-bed platform.

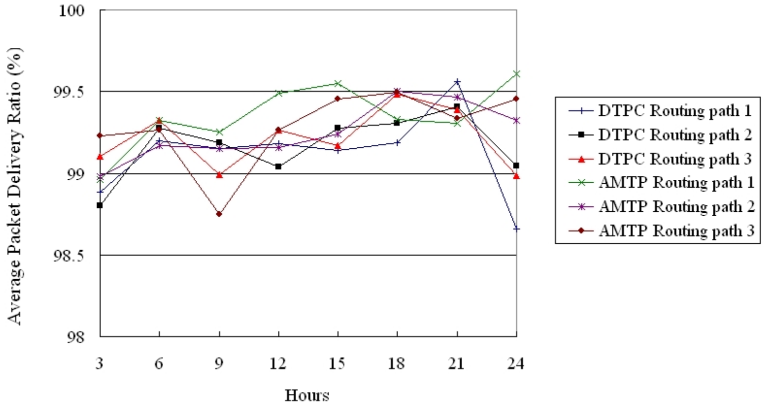


Fig. 9. The average one-hop packet delivery ratio of DTPC and AMTP.

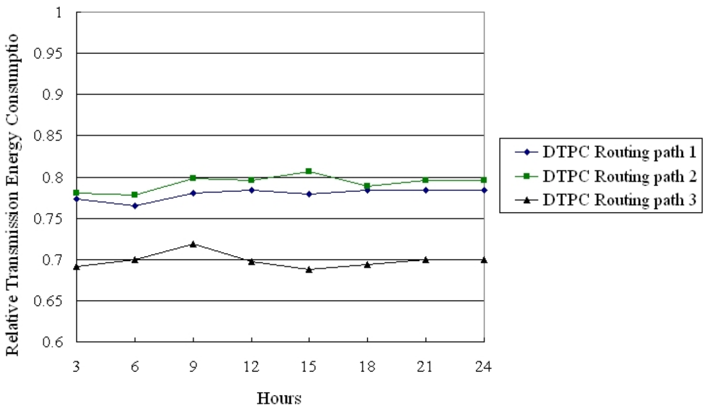


Fig. 10. The energy consumption ratio of our protocol with three routing paths.

In Fig. 9, we show the average one-hop packet delivery ratio of our DTPC and AMTP in three routing paths. The average packet delivery ratio of our DTPC and AMTP are 99.166% and 99.294%, respectively. The packet delivery ratio of our protocol is very close to AMTP.

In Fig. 10, we show the energy consumption ratio of our DTPC with three routing paths. The energy consumption ratio of a routing path is the total energy cost of using our protocol over the total energy cost of using AMTP. Here, we assume that all sensor nodes in our testbed are operating at the same supply voltage V(V) and send packets for the same time period Δt. Each time the sensor node sends a data message, the current consumption I(mA) for the radio transmission in each transmission power level can be determined in [20]. Therefore, the equation of energy cost (E_c) for sending one packet over one hop from the originating node is $E_c = I \cdot V \cdot \Delta t$. In Fig. 10, we can see that routing paths 1 and 2 consume more energy than routing path 3. This is because routing path 3 passes the corridor environment where exists few obstacles. Besides, the energy consumption of routing path 1 is a little difference with the routing path 2 since the power

Table 1. The percentage of transmission power levels used in each routing path of DTPC.

Routing path \ Power level	1	2	3	4	5	6	7	8
Routing Path 1	0 %	0 %	0 %	0 %	20.896 %	52.123 %	2.178 %	24.803 %
Routing Path 2	0 %	0 %	0 %	0 %	21.722 %	41.917 %	3.408 %	32.952 %
Routing Path 3	0 %	0 %	0 %	0 %	33.334 %	36.925%	7.477%	22.264 %

transmission level between two nodes is asymmetry. Table 1 shows the percentage of various transmission power levels used in each routing path of DTPC. According to the experiments, without sacrificing packet delivery ratio our protocol can save at least 20% energy cost compared to the nodes using the maximum transmission power to transmit their packets.

5. CONCLUSION

Power control in wireless sensor networks is an important issue due to the limited energy of the senor nodes. The power control protocol can help to decrease the transmission power of a node to a proper level and guarantee the link quality. In this way, we can prolong the lifetime of entire networks. In this paper, we proposed a distributed transmission power control algorithm with the initial phase and maintaining phase. The main purpose of initial phase is to find the proper initial transmission power for each neighboring node as soon as possible. The main purpose of maintaining phase is dynamically determining and adjusting the proper transmission power level with environmental change. In maintaining phase, the node adjusts its transmission power level for one neighboring node depending on the RSSI and LQI values.

We experiment and compare the performance of our DTPC algorithm with the AMTP on our testbed platform in the real environment. The experimental results show that our DTPC can save 20% ~ 30% energy consumption compared to AMTP. Beside, the DTPC can achieve at least 99% average packet delivery ratio between two hops which is very close to the AMTP.

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