CCI-Based Link Quality Estimation Mechanism for Wireless Sensor Networks under Perceive Packet Loss

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***Abstract*—This paper proposes a CCI-Based (Chip Correlation Indicator) link quality estimation mechanism for wireless sensor networks, which is used under the case of perceive packet loss. This mechanism studies on the relationship model between CCI and PRR (Packet Receive Rate) under the case of perceive packet loss, which is carried out on the foundation of doing analysis of the sending and receiving process of data frame and the factors which affect link quality. The building of the CCI-PRR relationship model is divided into two parts: the first is the building of CCI-SER (Symbol Error Rate) relationship model, and the second is the building of SER-PRR relationship model. During estimation period, nodes continuously track the CCI, and Kalman Filter is used to do denoising of CCI due to the large fluctuating range of the raw CCI. Then the denoised CCI is mapped into a local CCI-PRR mapping model to get the corresponding PRR. Experiment results have validated the correctness of the CCI-PRR mapping model, and the results also show that compared with counting-based PRR estimation mechanism, the mechanism proposed in this paper can use fewer probe packets to get a relatively accurate estimation value, it has the advantage of decreasing extra energy consumption caused by sending large number of probe packets.**

***Index Terms*—Wireless Sensor Networks, Link Quality, Estimation Mechanism, Kalman Filter, Perceive Packet Loss**

I. Introduction

Wireless sensor networks are distributed system, all sensor nodes are deployed randomly in the monitored area and then constitute to a network in wireless self-organization manner. Low power wireless RF signal (i.e. electromagnetic wave) is used in nodes' communication, and this will cause that the communication quality between nodes affected by many factors, such as wave reflection, wave diffraction, multi-path effects caused by wave reflection, the change of environment, and so on. All these factors lead the link to be random and instable.

A. Link Characteristics Introduction

In order to guarantee the network running efficiently and stably, people start to do researches on the link characteristics. De Couto et al. [1] find high variability in link quality, and argue that the widely accepted route protocol "Shortest path route protocol" works poorly as a result of the existence of variability of link. Then further research on link characteristics is done in [2] [3] by J. Zhao and R. Govindan. In [3], they use nearly 60 Mica motes to do research on link characteristics from medium access control layer and physical layer. Their experiment results show that half of the links experienced more than 10% packet loss, and one third more than 30%, and in harsher environments nearly 10% links are non-symmetry. Niels Reijers and Gertjan Halkes et al. [4] show that there is an area called "gray area" within the communication range. The communication quality in this area is very strange, it fluctuates all the time. Sometimes the link quality of the node far away from sender is better than the one nearby.

The characteristics of link can be summarized as follows:

- Directivity. The link quality in different directions is not the same i.e. in some directions it is good, while in other directions it is bad.
- Asymmetry. The link quality between node A and node B is asymmetric. E.g. the link quality from A to B is very good, but the link quality from B to A is medium or even bad.
- "Gray area". There is an area called "gray area" in the communication range of node. The link quality in this region changes continually. Sometimes the link quality of the nodes far away from the sender is better than the ones nearby.
- Irregular communication range. The shape of communication range of node is not a regular sphere.

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- Instability. The link quality between nodes is instability due to various factors such as interrupts from outside, the movement of node, and so on. This phenomenon is especially common to the nodes in "gray area".

B. Introduction of Current Link Quality Estimation

All the link characteristics mentioned above result in the instability of link. So, it is hoped that a simple way can be taken to do estimation of the link quality between nodes. Initially, people want do estimation of link quality through a relationship between distance and link quality. Pei Gang Sun and Hai Zhao et al. [5] get a relationship between distance and packet receive rate based on path loss model combined with free space lognormal shadow and the formula of bit error rate. But Gang Zhou et al. [6] argue that the link is not only instability but also directivity, i.e. in some directions the link are good, while others are bad. So it seems that the model only built on distance is not reliable. Yingqi Xu et al. [7] present a spatial correlation based weighted regression algorithm, which captures the spatial correlation of links between a sensor node and its neighbor nodes. It takes the directivity of link into account.

Reijers and Halkes et al. [4] show an estimation method based on RSSI (Receive Signal Strength Indicator). But their experiment results show that RSSI is very sensitive to the environment where nodes are deployed, so it is hard to form a unified standard. Woo and Culler et al. [8] use PRR (Packet Receive Rate) as metric to measure link quality, and propose a WMEWMA estimator. But Rodrigo Fonseca et al. [9] point that the PRR-Based estimation method will increase communication overhead. Meanwhile Jian Zhu et al. [10] also point that the real-time performance of the method based on PRR is not satisfactory.

With the introduction of Chipcon's CC2420 chip, there is one more measurement metric of link quality named LQI. LQI is defined as correlation value of the first 8 symbols of the received frame. It can be considered as a measurement metric of chip error rate [11]. It can reflect the channel quality by each packet. In [12], it is called CCI (Chip Correlation Indicator). The parlance of CCI is more suitable than LQI, because it not only indicate what the value is, but also indicates how to get the value. So this paper adopts the name CCI. The CCI measurement metric is researched in [10] [13] [14] [15]. In [10], a link quality estimation model based on CCI is proposed. With this model, the link quality can be inferred from the acquired CCI. They consider all packet loss as non-perceive packet loss. But the link packet loss can be divided into two kinds-- one is perceive packet loss and the other is non-perceive packet loss. Moreover their research just based on experiments, it makes that their estimation method seems not comprehensive. Pei Gang Sun and Hai Zhao et al. [15] propose mean RSSI and mean CCI measurement methods based on doing analysis of the problems of traditional link measurement methods. Meanwhile they have done a comprehensive research on their performance. Hai Zhao et al. [16] point that the link quality can be also influenced by frame length. And they propose a method to measure the link quality of WSN, which can avoid the influence caused by frame length.

An estimation method combined with physical layer, link layer and network layer is proposed in [9] by Rodrigo Fonseca and Omprakash Gnawali et al. In this method only four bits is used to reflect the link quality. Meanwhile they have analyzed the performance of the Four-Bit estimation in their experiment. The experiment results show that it can reduce packet delivery costs by up to 44% over current approaches and maintains a 99% delivery ratio over large, multi-hop test bed.

Recently a prediction model of link quality based on pattern matching has been proposed. And the principle of this method is that first node tracks and stores recent link quality and builds a time-series model of link quality. And then the time-series model is made as an input of pattern matching. With the pattern matching, it will select an optimal model as the recently predict model. And then the predict model is used to do estimation of link. Karoly Farkas et al. [17] figure out an implementation of this model named XcoPred.

II. WSN Link Quality Measurement Metric

Currently, the link quality measurement metric in wireless sensor networks fall into two categories: physical layer measurement metric and link layer measurement metric. The physical layer measurement metric has the one based on RSSI (Received Signal Strength Indicator) and the one based on CCI (Chip Correlation Indicator). The advantages of physical layer estimation are that it can reflect the link quality by each packet, and it reacts quickly to the change of link. But normally the physical layer estimation is not stable. The link layer measurement metric has the one based on PRR (Packet Receive Rate). The advantage of link layer estimation is that it can give a more accurate estimation of link. But it needs lots of probe packets and reacts slowly to the change of link. The distribution of RSSI, CCI and PRR in OSI is shown in Fig.1.

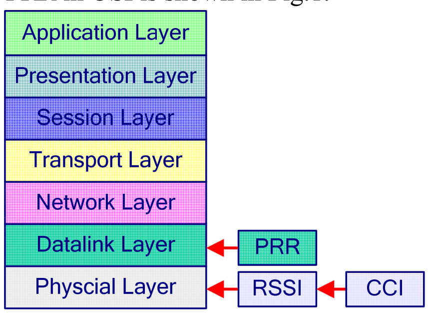

Figure 1. The distribution of RSSI, CCI and PRR in OSI

In mobile networks, RSSI is often used as the indication of link quality. RSSI is the strength of the signal. Whether the receiver can correctly receive signal depends on the minimum signal to noise ratio of the receiver. To a certain noise power, the stronger of the signal, the larger of signal to noise ratio, and the larger probability of filtering the signal out of the noises. From the information mentioned above, it can be found that RSSI can reflect the link quality in some degree. The acquisition of RSSI in CC2420 is shown as follows: first CC2420 will take sample of the first 8 symbol cycle (128μs) of the data frame to acquire the RSSI during the receiving process. And then CC2420 will calculate the mean value of RSSI and store it in the register RSSI_VAL of CC2420. The RSSI stored in the RSSI_VAL register should be further converted to the power P at the RF pins.

It is difficult to measure link quality accurately by using RSSI, because low power radio signal is used in wireless sensor networks and it highly vulnerable to the environment.

Meanwhile, with appearance of Chipcon's CC2420 chip, there is one more measurement metric of link quality named CCI. According to CC2420 datasheet, DSSS (Direct Sequence Spread Spectrum Technology) is used during the data transmission process. In the sender side, data will be sent out in the form of chip sequence. During the receiving process of data frame, the received chip sequence will be made as an input of comparator. Then the comparator will select the one which is most similar to the received chip sequence from local chip-to-symbol mapping table as the actual chip sequence transmitted by sender. In the end, the selected chip sequence will be transformed to symbol according to the local symbol-to-chip mapping table. The CCI is actually the correlation value between the received chip sequence and the one in the symbol-to-chip mapping table transmitted by the sender. In some degree, it can also be looked as a measurement of the "chip error rate" [11].

The CCI is acquired by taking sample of the first 8 symbols following the start of frame delimiter. It includes the following three fields: frame length field, frame control field and data sequence number field. During the receiving process, the receiver computes the correlation value for each symbol of the first 8 symbols. At the end of receiving process the receiver will compute the mean CCI of the first 8 symbols and take the average correlation value of the first 8 symbols as the link quality indicator. The range of CCI is normally from 50 to 110.

The link layer measurement metric PRR gives estimation on link quality by doing statistics on the success and failure state of each packet transmission. According to the different acquisition methods, it falls into two categories: active probe method and passive probe method. Lots of probe packets should be counted for the method based on PRR. The communication overhead will be increased by large number of probe packets. Furthermore the real-time performance will be influenced.

According to all the information mentioned above, this paper proposes a CCI-Based link quality estimation mechanism for wireless sensor networks on the foundation of the above researches, which is used under the case of perceive packet loss. With this mechanism, the link quality between nodes is available, and the upper-layer protocol can make use of the link quality between nodes to make some adjustments to the network to guarantee that it can run efficiently and stably. This mechanism does research on CC2420, and builds a mapping model of CCI-PRR based on doing analysis of the sending and receiving process of data frame and the factors which affect link quality. During estimation, nodes continuously track the CCI, and Kalman Filter is used to do denoising of CCI due to the large fluctuating range of the raw CCI. Then the denoised CCI is mapped into a local CCI-PRR mapping model to get the corresponding PRR. It relates the physical layer estimation with the link layer estimation; it works on both physical layer and link layer. So it has the advantages of them.

III. LINK ESTIMATE MECHANISM UNDER PERCEIVED PACKET LOSS

Packet loss in wireless sensor networks can be divided into the following two categories: perceive packet loss and non-perceive packet loss.

Definition 1: After the recipient has received packet from the sender, there is something wrong with the received packet, so the packet will be dropped by recipient. The packet loss occurs in this case is called perceive packet loss.

Definition 2: During the sending process of the sender, the recipient has received nothing. It does not perceive that the sender is sending data. The packet loss occurs in this case is called non-perceive packet loss.

This paper focus on doing research on the first case (perceive packet loss). In order to get a further understanding of the cause of wrong data frame, the sending and receiving process of data frame in CC2420 should be analyzed first.

A. Analysis of TheFailure Transmission of Data Frame

For chip CC2420, data is transmitted in frame which is composed of many bytes. During the transmission process, each byte is divided into two symbols. Then each symbol is mapped into chip sequence through a local symbol-to-chip mapping table. And finally the chip sequence is transmitted through an O-QPSK modulation. The whole process is shown in Fig.2. During the receiving process, the received chip sequence will be made as an input of comparator in CC2420. Then the comparator will select the one which is most similar to the received chip sequence from local chip-to-symbol mapping table as the actual chip sequence transmitted by sender. Then the selected chip sequence will be mapped into symbol according to local symbol-chip sequence table.

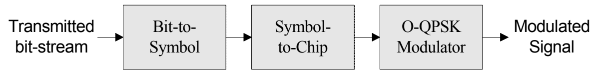

Figure 2. The process of data transmission[11]

From above analysis, it is clear that the reason of the failure transmission of data frame includes the following factors: wave reflection, wave diffraction, multi-path effects caused by wave reflection, and the interference from outside. All these factors will cause the change of chip sequence. The changed chip sequence may make comparator select other chip sequence rather than the one transmitted by sender. And the wrong selection will result in the mapping error in the chip sequence to symbol mapping phase, and finally lead to the failure transmission of data frame. The cause chain of frame error is shown in Fig.3.

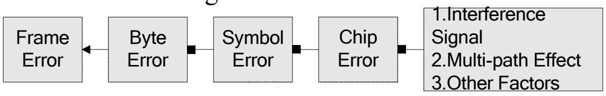

Figure 3. The chain of data frame error cause

With above analysis, the perceive packet loss model will be constructed as follow.

B. The Building of Perceive Packet Loss Model

Perceive packet loss i.e. the recipient has successfully perceived the synchronization head, but there are some wrong symbols in the frame length field or MAC data unit field or both of them. This will lead to the discarding of data frame in the recipient side (the sketch of IEEE 802.15.4 frame format is shown in Fig.4). According to the different position of the error symbols in frame, the frame error can be divided into two categories: frame length field error and MAC data field error. The frame length field error can be further divided into early truncation of frame caused by the decrease of frame length and delay truncation caused by the increase of frame length. No matter where the error occurs, if there is symbol error, the frame is error, and it should be discarded. According to the analysis above, the relationship between SER and PRR is going to be created.

Figure 4. IEEE 802.15.4 Frame Format[11]

1) the building of SER-PRR relationship

Definition 3: L is the frame length (the total length of frame length field and MAC data field); PLR is the packet loss rate; PRR is the packet receive rate; FER is the frame error rate; and SER is the symbol error rate.

From above analysis, it is known that frame is composed of multiple bytes and each byte is composed of two symbols. In order to make the frame transmitted correctly, all the symbols in the frame should be transmitted correctly. According to this principle, the relationship between FER and SER can be deduced as (1).

$$FER = 1-(1-SER)^{2L} \qquad (1)$$

The calculation formulas of SER and FER are shown in (2) and (3):

$$SER = \frac{Sum(Error\_Symbol)}{Sum(Total\_Symbol)} \times 100\% \qquad (2)$$

$$FER = \frac{Sum(Error\_Frame)}{Sum(Total\_Frame)} \times 100\% \qquad (3)$$

Where $Sum(Error\_Symbol)$ and $Sum(Error\_Frame)$ are the total number of error symbol and error frame. $Sum(Total\_Symbol)$ and $Sum(Total\_Frame)$ are the total number of symbol and frame. All of them are measured under the case of perceive packet loss.

From (1), it can be known that the frame error rate is not only influenced by symbol error rate but also by the frame length. The correctness of (1) will be validated by follow-up experiment which is shown in next part of this paper.

Under the case of perceive packet loss, the only cause of packet loss is the frame error. So PLR is equivalent to FER and (1) can be overwritten as (4).

$$PLR = FER = 1-(1-SER)^{2L} \qquad (4)$$

The relationship between PRR and PLR can be given by (5).

$$PRR = 1-PLR \qquad (5)$$

Combined with (4) and (5), the calculation formula of PRR can be deduced as (6):

$$PRR = (1-SER)^{2L} \qquad (6)$$

According to above analysis, when the length of frame is fixed, the packet receive rate (PRR) is only influenced by symbol error rate (SER). From foregoing, it can be known that symbol error rate is influenced by chip error rate (CER). According to the introduction of CC2420 datasheet, CCI can be considered as a measurement of chip error rate (CER). If the relationship between CCI and SER is available, combined with (6), the relationship between CCI and PRR can be available. The key issue lies on the acquisition of the relationship between CCI and SER. Before making analysis of the relationship between CCI and SER, the performance of CCI is analyzed first.

2) the change of CCI under certain distannce

In order to do analysis of CCI, experiment has been done. In the experiment, CCI is acquired from packet directly without any process in the recipient side. The transmission rate is set to 25packets/sec, and 1400 packets have been tracked in the experiment. During the experiment the distance between sender and recipient is fixed. The change of raw CCI under certain distance is shown in Fig.5 with gray line. From Fig.5, it can be found that the range of raw CCI is so large that it is difficult to be used to reflect the link quality by a real-time value.

So kalman filter model is introduced to do denoising of CCI in this paper. The kalman filter model not only takes the mean and variance into account, but also the change of process. Kalman filter model is a recursion process with time, and iterative approach is used to reduce the variance by Kalman filter, so there is no need to store large amounts of historical CCI. The filtered value can be acquired once the new data is available. From the information mentioned above, it is known that the real-time performance of this model is good. The kalman filter model of CCI is going to be built as follows.

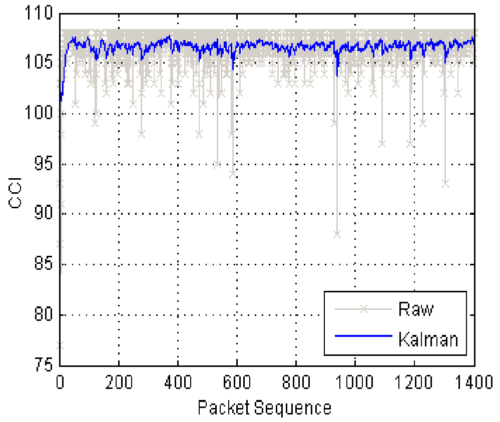

Figure 5. The change of CCI under certain distance

3) the building of kalman filter model

A random linear discrete system is introduced first as follows:

$$x_k = Ax_{k-1} + Bu_k + w_{k-1} \quad (7)$$

$$z_k = Hx_k + v_k \quad (8)$$

Where x_k is the value that to be estimated at time k and z_k is the measured value at time k. The noise in the process is modeled with Gaussian random variable w_{k-1}, $p(w) \sim N(0,Q)$. The measurement noise is captured by v_k, $p(v) \sim N(0,R)$. Q and R represent process noise variance and measurement noise variance respectively. The covariance between w_{k-1} and v_k can be depicted by $Cov\{w_{k-1}, v_k\} = 0$. In (7), A is a state migration matrix, which relates the state at the previous time k-1 to the state at the current time k. Matrix B relates the optional control input to the state k. Matrix H relates the state to the measurement z_k.

In practice, x_k in the experiment is the CCI value to be estimated at time k and z_k is the CCI measured value at time k. In short time, CCI is considered to be constant i.e. the state does not change from step to step, so A is set to 1. There is no control input of this system, so u_k is set to 0. And the CCI measured value is directly gotten from estimation value, so H is set to 1. According to the setting, (7) and (8) can be further overwritten as follows.

$$x_k = x_{k-1} + w_{k-1} \quad (9)$$

$$z_k = x_k + v_k \quad (10)$$

According to the system built on (9) and (10), the update formulas are given as follows:

- Time Update:

$$\hat{x}_k^- = \hat{x}_{k-1} \quad (11)$$

$$P_k^- = P_{k-1} + Q \quad (12)$$

- Measurement Update:

$$K_k = P_k^-(P_k^- + R)^{-1} \quad (13)$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - \hat{x}_k^-) \quad (14)$$

$$P_k = (1 - K_k)P_K^- \quad (15)$$

Where $\hat{x}_k^-$ and $\hat{x}_k$ represent the priori and posteriori estimates of CCI respectively. P_k^- and P_k represent priori and posteriori estimate error variances respectively. K_k is kalman gain.

In order to make this kalman filter start to work, the initial value of Q, R, $\hat{x}_0$ and P_0 need to be set first. The selection of Q only influence the convergence speed, it will not influence the accuracy. In the experiment, it is set with the variance of $x_k - x_{k-1}$ over a set of test transmissions. In practical, R is difficult to get. In this experiment, it is set with the variance of CCI. In this case, the filter can be asymptotically optimal, no matter what the initial value of $\hat{x}_0$ and P_0. In this experiment $\hat{x}_0$ is set with the first packet CCI value, P_0 is commonly set with Q [18].

The CCI processed by kalman filter is shown in Fig.5 with blue line. According to Fig.5, it can be found that the fluctuation range is obviously smaller after kalman filter processing. In some degree, it reduces the influence of the noise, and it is more suitable to reflect the link quality than raw CCI.

On the foundation of above research, the relationship between CCI and SER is going to be researched next.

4) the building of CCI-SER relationship model

The experiment scheme will be mentioned in experiment part of this paper. The value of CCI, SER and FER are tracked in each experiment. And the distribution between CCI and SER acquired from experiments is shown as follows:

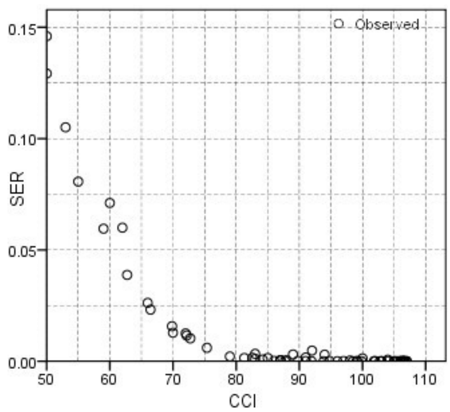

Figure 6. The distribution between CCI and SER

In Fig.6, it can be found that the range of CCI is from 50 to 108, the SER is nearly stable at 0 when CCI is lager than 100. So the CCI is divided into two parts: the first is $CCI >= 100$, and the other is $CCI < 100$. For the case $CCI >= 100$, it is assumed that SER is 0. For the case $CCI < 100$, from Fig.6, it can be found that there is some orderliness of the CCI-SER distribution. So curve fitting is done for the case $CCI < 100$. During the curve fitting, many models are used such as logistic model, cubic model, growth model, power model and so on. From the curve fitting of all these models, it is found that the exponential model fits the distribution best. The result of curve fitting is shown in Fig.7.

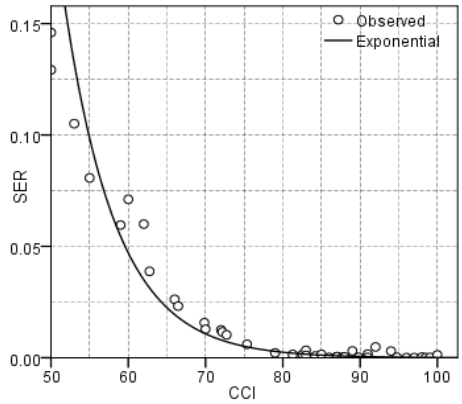

Figure 7. The curve fitting of CCI and SER

The curve formula of exponential model in Fig.7 is given by (16).

$$\mathrm{SER} = 331.182023 \times e^{(-0.147655 \times \mathrm{CCI})} \quad (16)$$

Combined with the case $CCI >= 100$, the relationship model between CCI and SER can be summarized by (17).

$$SER = \begin{cases} 0 & CCI >= 100 \\ 331.182023 \times e^{(-0.147655 \times \mathrm{CCI})} & CCI < 100 \end{cases} \quad (17)$$

Based On the formulas (1), (4) and (17), the FER i.e. PLR can be acquired according to the denoised CCI. Combining with (5), the PRR can be acquired.

Not only the CCI-SER model is acquired in the experiments, but also the relationship between FER and SER is validated. The distribution of SCR (Symbol Correct Rate) and FCR (Frame Correct Rate) is shown as follows.

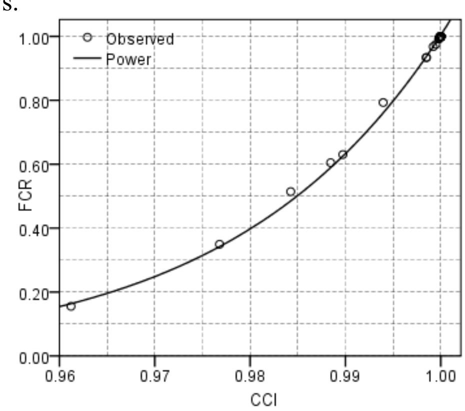

Figure 8. The curve fitting of SCR and FCR

The power curve in Fig.8 is acquired from curve fitting. The formula of this curve is given by (18).

$$FCR = 1.004187 \times SCR^{45.854897} \quad (18)$$

The relationship between FCR and FER, SCR and SER are shown as follows.

$$FCR = 1 - FER \quad (19)$$

$$SCR = 1 - SER \quad (20)$$

According to (18), (19) and (20), the formula of FER can be given by (21).

$$FER = 1 - 1.004187 \times (1 - SER)^{45.854897} \quad (21)$$

In practical experiment, the frame length is 23 bytes, according to (1), the FER can be given by (22).

$$FER = 1 - (1 - SER)^{46} \quad (22)$$

From the comparison of (21) and (22), it can be found that the formula acquired from experiment results is very close to the one that inferred from theory. In some degree, the experiment result validates the correctness of (1).

IV. EXPERIMENT

The nodes used in the experiments are Telosb series nodes. This series node is powered by two AA batteries, and equipped with a 16 bits MSP430 microprocessor with 10kB RAM and a CC2420 wireless communication chip which is designed according to IEEE 802.15.4 criterion. Temperature, light, humidity and sensor onboard antenna are integrated on the node. It works on non-commercial 2.4 GHz, a globally compatible ISM band. Furthermore there are 8 different transmission powers. During the sending process, the transmission power can be dynamically changed by software. The data transfer rate is up to 250 kbps.

The block diagram and the reality figure of Telosb node are shown in Fig. 9. And the capability parameters of telosb are shown in table I.

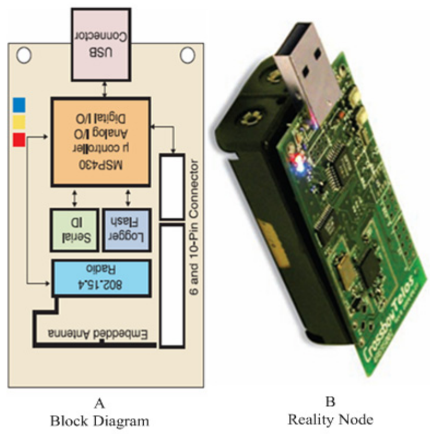

Figure 9. Telosb

TABLE I.
TELOSB CAPABILITY PARAMETERS

TELOSB	Capability parameter
Microprocessor	16-bit RISC
Program Memory	48k bytes
RAM	10k bytes
RF	2400MHz-2483.5MHz
Power	-24dBm~0dBm
Data rate	250Kbps

The system running on the node is TinyOS. TinyOS is a small, open-source, energy-efficient software operating system developed by UC Berkeley. It is the system designed for wireless embedded sensor networks. It features a component-based architecture which enables rapid innovation and implementation. The component library of TinyOS includes network protocols, distributed services, sensor drivers, and data acquisition tools.

The programming language of TinyOS is NesC. NesC is an extension of C language. Compared with C, NesC has the advantages of convenience and reliability.

The experiments are conducted outdoor with a pair of Telosb nodes. Node TX-1 represents the sender, and RX-1 represents the recipient. In normal situation, the packet which does not pass CRC checkout will not be submitted to up-layer application. But in these experiments, the error packets need to be analyzed, so the low-layer receiving program of Telosb node is modified to keep the error packets. The transmission rate of node is set to 10packets/sec.

During the experiments, RX-1 is connected to the PC through USB port. In order to get different CCI value, the distance between node TX-1 and node RX-1 will be changed during experiments. PC will store the raw CCI, denoised CCI and the responded real perceive packet receive rate for each experiment. During the experiments there is no human interference. The outdoor test-bed setup is shown in Fig. 10.

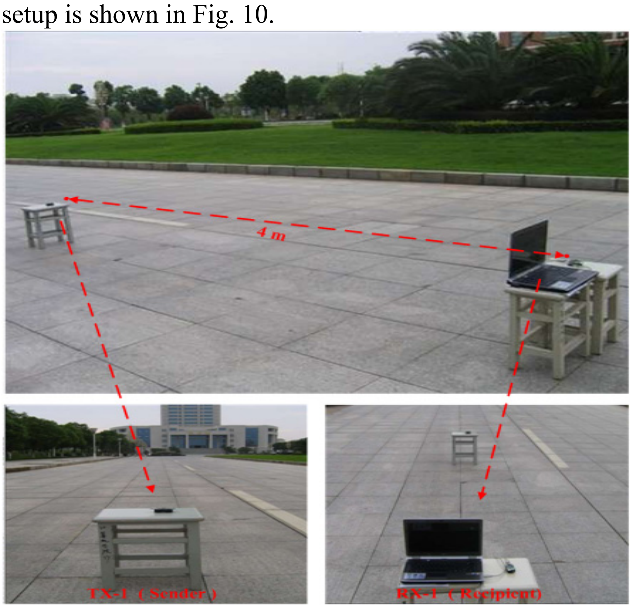

Figure 10. Outdoor test-bed setup

V. RESULTS AND ANALYSIS

A. *The validation of perceive packet loss model*

Experiments have been made to validate the correctness of the perceive packet loss model. The comparison between theoretical value and measured value of perceive packet receive rate is shown in Fig.11.

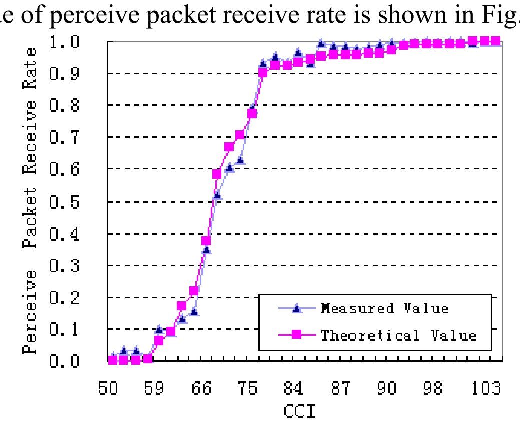

Figure 11. The comparison of measured value and theoretical value

In Fig.11, the measured value is gotten from practical experiments, and the theoretical value is calculated from perceive packet loss model. From Fig.11, it can be found that the measured value tally with the theoretical value mostly. It is assumed that if the sample is large enough the measured value will superpose with the theoretical value. So in some degree, it validates the rationality of the perceive packet loss model proposed in this paper.

B. *The analysis of the performance of estimation mechanism*

Not only the rationality of the perceive packet loss model is validated in this paper, but also the performance of the estimation mechanism is analyzed.

A comparison among R_CCI, K_CCI and PRR is shown in Fig.12. In Fig.12, R_CCI is the case that doing estimation with raw CCI according to the model proposed in this paper, K_CCI is the case that adopting the CCI denoised by kalman filter to do estimation according to the model proposed in this paper, and PRR is the estimation method based on counting-based.

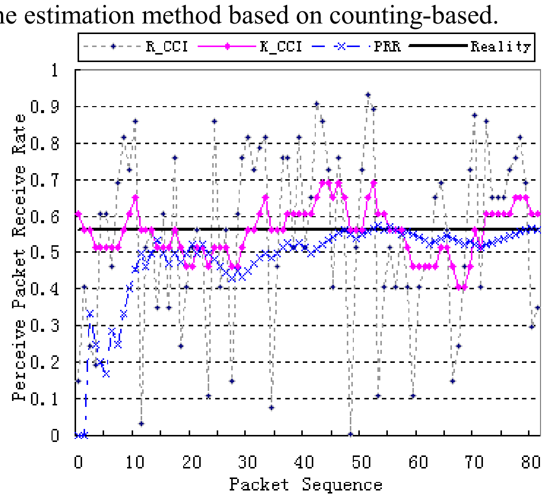

Figure 12. The comparison of three mechanisms

The distribution of perceive packet receive rate in these three cases is shown in Fig.12. The Reality in Fig.12 indicates the real perceive packet receive rate. For R_CCI and K_CCI, the x-axis represents the packet sequence number. For the case PRR, it represents the number of probe packets. E.g. for the case PRR, 40 on the x-axis indicates that 40 probe packets have be counted to calculate PRR.

Form Fig.12, it can be found that the fluctuation range of R_CCI is so large (from 0 to 0.9) that is hard to use the raw CCI to do estimation of the link directly. This paper does not recommend using the raw CCI directly. For K_CCI, it can be found that the perceive packet receive rate fluctuates near the real perceive packet receive rate all the time. And for the case PRR, it can be found that the perceive packet receive rate is more and more close to the real value with the increase of probe packets. But the cost is the extra energy consumption caused by sending large number of probe packets. Meanwhile the performance of K_CCI and PRR is analyzed. The estimation error comparison between PRR and K_CCI is shown in Fig.13.

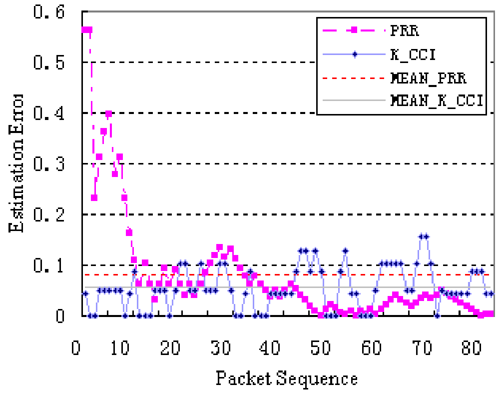

Figure 13. The estimation error comparison between PRR and K_CCI

In Fig.13, MEAN_PRR indicates the mean estimation error of PRR, which is about 8.1%; MEAN_K_CCI indicates the mean estimation error of K_CCI, which is about 5.6% lower than MEAN_CCI. From the figure, it can be found that when the number of probe packets is small (such as 10), the estimation error is very large for PRR (about from 0.1 to 0.55). But for K_CCI, the estimation error fluctuate in the range from 0 to 0.1 mostly, it is more stable than PRR. For PRR, with the increment of probe packets the estimation error will decrease. From Fig.13, it also shows that for PRR, about 40 probe packets need to be counted to achieve the mean estimation error of K_CCI (5.6%), but for K_CCI, it needs only few packets. So compared with the estimation mechanism based on PRR, the estimation mechanism proposed in this paper can use fewer probe packets to get a relatively accurate estimation value of link quality. It has the advantage of decreasing the extra energy consumption caused by sending large number of probe packets.

VI. Conclusion

First, this paper gives a conclusion of the link characteristics and an introduction of current link quality estimation method. On the foundation of the former researches, this paper proposes a CCI-Based (Chip Correlation Indicator) link quality estimation mechanism for wireless sensor networks, which is used under the case of perceive packet loss. Due to the large fluctuation range and instability of raw CCI, this paper introduces a kalman filter to process the raw CCI. Then, a relationship model between CCI and PRR has been built based on theoretic analysis and experiments. Meanwhile the rationality of this model has been validated through practical experiments. During estimation period, nodes continuously track the CCI, and denoise it with Kalman Filter. Then the denoised CCI is used to get the corresponding PRR according to a local CCI-PRR mapping model. Experiment results show that compared with the estimation mechanism based on PRR, the estimation mechanism proposed in this paper can use fewer probe packets to get a relatively accurate estimation value of link. So it can decrease the extra energy consumption cause by sending large number of probe packets.

With coming work, another kind of packet loss (non-perceive packet loss) in wireless sensor networks is going to be considered.

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