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MuZi: Multi-channel ZigBee Networks for Avoiding WiFi Interference

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***Abstract*—In Cyber-Physical system (CPS), different wireless technologies are used, which results in cross-technology communication interference. Specifically, ZigBee networks share the 2.4GHz ISM band with WiFi but have much lower transmission power. Thus, the ZigBee networks inevitably suffer the interference from WiFi Networks. This paper focuses on the locality of WiFi interference and proposes an interference avoiding approach based on multi-channel for ZigBee networks called MuZi. MuZi has three basic mechanisms: interference assessment, channel switch and connectivity maintenance. The proposed interference assessing approach jointly considers the degree of intensity and density and achieves a much actual relationship between WiFi interference and link quality. Based on this finding, the better working channel for each node is determined. A connectivity maintenance approach is also proposed to ensure the connectivity of the nodes to the sink. Our extensive experiments on a testbed of 802.11 embedded nodes and 802.15.4 TelosB motes show that, under the existence of WiFi interference, MuZi can achieve 3.3 times throughput than the traditional single-channel method.**

***Index Terms*—CPS, Sensor Networks, ZigBee, Multi-Channel, Interference Avoidance**

I. INTRODUCTION

Recently, the cyber-physical system (CPS) has drawn increasing attentions [1]; it aims at integrating computing, communication and storage capabilities with monitoring and or control of entities in the physical world. In the design of CPS, various wireless communication technologies have been witnessed, such as WiFi, ZigBee and Bluetooth [2,3]. Given the scarce availability of RF spectrum, many of these technologies are forced to use the same unlicensed frequency bands. For example, IEEE 802.11 (WiFi), IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (ZigBee) all share the same 2.4 GHz ISM band.

Sharing the same frequency band definitely leads to cross technology interference. It will cause intermittent network connectivity, packet loss and ultimately result in lower network throughput and higher communication latency. Specifically, ZigBee and WiFi networks are very likely to be colocated within the interfering range of each other. However, because of the lower transmit power and some other disadvantageous parameter settings (eg. shorter back off time slot), ZigBee is affected more severely by WiFi networks. With the growing popularity of WiFi, the situation will be even worse. Thus, under the existence of WiFi interference, how to improve communication performance of IEEE 802.15.4 is becoming a crucial issue.

There have been some studies about how to avoid WiFi interference in IEEE 802.15.4 network [4,5]. The conclusion of those studies was that the only way to mitigate such interference for the 15.4 network is to avoid the channels occupied by 802.11.

Furthermore, there are mainly two ways to achieve interference avoidance: global channel assignment and local channel assignment. In a global channel assignment scheme, all sensor nodes share the same channel (planed or not planed) to communicate with each other. This scheme has a fatal drawback: because of spatial locality of WiFi interference, some of the local areas may suffer severe degraded performance, thereby degrading the entire network performance. Moreover, with the increasing WiFi deployment, it's almost impossible to find the globally unoccupied channel. In local channel assignment schemes, different nodes in a sensor network, or the same node over different time, will use different 15.4 channels to avoid interference from nearby WiFi sources. Apparently, local schemes comply with the locality of WiFi deployment naturally.

However, these schemes face two main challenges: (1) How to assess the severity of WiFi interference. Sometimes, there is no need to avoid interference when it is mild and acceptable. But when it suffers severe WiFi interference, a node has to choose a new channel to avoid interference and the new channel should be relatively clear in its vicinity. All these decisions require a node to know the given channel's degree of interference. (2) How to coordinate channel selection among 15.4 senders and receivers. Local WiFi environment changes will lead to channel switch, some kind of coordination is needed to ensure that senders and receivers are still able to communicate properly.

This paper focuses on the above two challenges and proposes a novel solution. The paper makes the following contributions:

1). A novel method for assessing the severity of WiFi interference is proposed. Contrary to the current solution,

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the proposed method jointly considers the intensity and density of WiFi interference and thus can represent the effect of WiFi interference on the link performance of 15.4 more accurately.

2).We further augment the multi-channel mechanism to ZigBee networks and propose a protocol called MuZi for interference avoidance. Using the proposed interference assessment method, the ZigBee nodes assess the level of the local interference that they are suffering and then choose a new working channel with lower interference if necessary.

3). We make extensive experiments on a testbed of 802.11 embedded nodes and 802.15.4 TelosB motes Experimental results show that, under the existence of WiFi interference, our multi-channel data collection service can achieve 3.3 times throughput than the traditional single-channel method.

The remainder of the paper is organized as follows. The related work is presented in Section II. Section III discusses the limitations of the traditional PRR-SINR(Packet Reception Rate and Signal to Interference-plus-Noise Ratio) model and introduces a new interference assessment method. Section IV presents the design and implementation of Multi-channel ZigBee networks, called MuZi. Section V evaluates the proposed interference assessment method and MuZi protocol. Section VI concludes this paper.

II. RELATED WORK

Wireless sensor networks will play an important role in Cyber-Physical system, whose applications typically fall under sensor-based systems and autonomous systems. For example, many wireless sensor networks monitor some aspects of the environment and relay the processed information to a central node. Many different wireless communication technologies, such as ZigBee and WiFi, have been witnessed recently to be deployed in more and more applications. Thus, the cross technology interference has draw attention of the researchers. Now, the WSN community has acknowledged the impact of WiFi interference on WSN applications in various settings.

Roughly, the current research can be classified as the following three categories based on the research points:

The works in the first category are focus on the mechanism or principle of interference. An empirical results was found in [4] in a hospital setting. The results show that running CTP on a 15.4 network that overlapped with an active 802.11 channel decreased the end to end goodput by a factor of three.

The impact of 802.11 interference on ZigBee networks was studied in [5] and the authors found that the position distribution of bit errors in 15.4 packets is temporally correlated with 802.11 traffic. The authors in [6] found that 15.4 packet loss as high as 87%, with an 802.11b sender located in between two 15.4 nodes five meters apart.

Currently, under the existence of WiFi sources, the existing works predict 15.4 link performance based on SINR. A passive interference measurement method based on the PPR-SINR model is proposed in [6]. However, performance prediction model solely based on SINR is inaccurate.

The second kind of works focuses on how to avoid the WiFi interference for ZigBee networks. The common approach for 802.15.4 networks to mitigate 802.11 interference is to switch the network to channels that do not overlap with an active 802.11 channel.

According to IEEE 802.15.4 specification, the coordinator can scan the energy level in each channel so that the quietest channel could be chosen. However, all the nodes will work with the same channel and thus can not avoid the interference from WiFi hotspots which varies in different space over different time. In [7], Adaptive Frequency Hopping (AFH) is proposed for Bluetooth and WiFi coexistence. In [8], the authors proposed a distributed channel selection mechanism that detects 802.11 interference using periodic RSSI samples. However, these works did not consider the locality of interference and thus can not provide a good link performance. Moreover, static channel assignment may not work as planned due to node mobility and incremental WiFi deployments.

There are also some works focusing on the dynamic channel assignment schemes. Different nodes in a sensor network, or the same node over different points in time, will use different 15.4 channels to avoid interference from nearby WiFi sources. However, accurately assessing the interference is a key problem. The current methods do not present efficient method. Our paper aims to fill this gap and proposes a novel method.

Recently, more and more researchers found that improving the coexistence of 15.4 and 802.11 networks is beneficial to the spectrum efficiency. Through the statistical analysis of data traces, WiFi frames are highly clustered and the arrival process of clusters has the feature of self-similarity. Based on this find, the authors in [9] proposed a method to predict the length of white space in WiFi traffic. The ZigBee intelligently adapts frame size to maximize the throughput efficiency while achieving assured packet delivery ratio. Literature [10] designed a BuzzBuzz protocol to mitigate WiFi interference through header and payload redundancy. These methods are complementary to our method.

III. INTERFERENCE ASSESSMENT: THEORY AND METHOD

In this section, we will firstly introduce related theory about interference and analyze the limitation of PRR-SINR model. Then a novel method for accurately assessing WiFi interference is proposed. This interference assessing method takes into account the intensity and density of interference to overcome the limitation of PRR-SINR model.

A. *Theory of Performance Prediction Model*

Currently, under the existence of WiFi sources, the PRR-SINR[6] model is the most commonly used to predict packet reception rate of 802.15.4 link. This model is based on the following assumption: When interference exists, SINR and the proportion of time occupied by interference are both constant.

In essence, any performance prediction model based on SINR, is taking bit error rate (BER) as a starting point to get the desired performance metric via a series of complicated calculations. Here we will take packet reception rate (PRR) for example, to briefly explain how to obtain the PRR gradually from BER[11].

In the specification of IEEE 802.15.4, the PHY at 2.4 GHz uses offset quadrature phase shift keying (OQPSK) as the modulation model. Denote that the E_b/N_o is the ratio of average energy per information bit to the noise power spectral density at the receiver input, in the case of an additive white Gaussian noise (AWGN) channel. According to [12], the BER, denoted as P_B, can be expressed as

$$P_B = Q(\sqrt{\tfrac{2E_b}{N_o}}) \tag{1}$$

where Q(x) is

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp(-\frac{u^2}{2}) du \tag{2}$$

Roughly, E_b/N_o can be approximated using SINR.

Conflict takes place when both 802.11 and 802.15.4 send data at the same time. If the distances of the sender and WiFi sources from the receiver are all known in advance, combing with the existing wireless signal attenuation model, we can estimate the SINR when conflict happens. However, conflict does not always happen. Therefore, the conflict time ratio needs to be estimated to calculate the PRR. Assuming that WiFi and 802.15.4 send data as soon as possible and CSMA is disabled, we can easily estimate the proportion of conflict time given the parameter settings (SIFS, DIFS etc) from the specification document.

Then following above calculations, the probability of one bit error suffering WiFi interference could be figured out. Let's assume that 15.4's average packet length is L bytes, we can further compute packet error rate (PER) and finally the PRR.

From the introduction, we can see that the process not only involves a large number of approximation calculations, but also makes a great deal of idealized treatment. Moreover, it has to keep *SINR* and the conflict time ratio constant to get a stable probability of bit error. On the one hand, the complicated calculation process leads to inaccuracy in the final estimate. On the other hand, it is not in accordance with the dynamic nature of WiFi. In conclusion, we believe that any performance prediction model solely based on *SINR* is imprecise and inaccurate.

Here we summarize the limitations of PRR-SINR:

1) Require a stable interference environment: the constant *SINR* and conflict time ratio. At present, almost all researchers, who utilize PRR-SINR model to predict link performance, provide a full load WiFi as interference source. Their aim is to create a stable interference environment. However, due to the dynamic and mobility nature of wireless communication, *SINR* and the conflict time ratio are both instantaneous values and vary over time. In general, PRR-SINR model is only suitable to predict link performance in the static environment, not for a real dynamic environment.

2) SINR itself is difficult to obtain. In reality, it is often impossible to obtain location information of all interference sources. Furthermore, although being able to perceive the local signal energy, wireless nodes can not tell whether the signal is from sender or from interference source.

B. The Proposed Assessment Method

We have the common sense on interference that it involves not only intensity but also density. In fact, *SINR* is only an intensity indicator and the conflict time ratio is a density indicator. Only the combination of these two aspects can the severity of interference be assessed accurately. Besides considering the characteristics of resource-constrained that embedded devices have, we believe that the interference assessment metric should respond promptly to environment change and be involved with less calculation and overhead.,

In order to represent the intensity and density of interference, we choose a two tuple <u,v> as interference indicators, where u is a density indicator and v is an intensity indicator. **Given the <*u*, *v*> pair, we can distinguish between different interference by comparing *u* first and then *v* if *u* ties.** We choose interference density as the primary key because that interference signal rarely occupying the channel has little effect on the original link's performance, even if it is very fierce.

We define the channel occupancy rate (COR) as the **TIME** ratio occupied by WiFi interference. It is similar to the conflict time ratio, but could be easily approximated. In our method, we choose COR as the density indicator.

Received Signal Strength Indicator (RSSI) is the common way to represent the signal energy in the local environment. In no interference environment, almost all RSSI readings are below a specific value H. Therefore we can assume that all RSSI readings higher than H were from WiFi interference, and we choose the average of these RSSIs greater than H as the intensity indicator.

Taking H as the threshold, the <u,v> calculation process is as follows:

(a) We sample RSSI reading periodically, collecting W RSSI readings each round.

(b) Count the number of RSSIs (>H) as N and calculate the average A of the RSSIs (also >H).

(c) The final indicator pair <u,v> is <N/W, A>, where N/W is used to approximate COR and A as the intensity indicator.

The <u,v> pair only represents the interference information for one round. However, the interference varies over time. In order to predict future situation and quickly respond to change, we borrow exponentially weighted moving average (EWMA) technology which is used by wired network to estimate round-trip time. Thus, u and v is processed respectively as follows:

$$X = (1-\alpha) * X + \alpha * X' \qquad (3)$$

Here, X' is the value for current round and X is the EWMA value. In this paper, we set $\alpha = 0.125$ empirically.

Our method has the required features. The only overhead is to read RSSI register, which is a very cheap operation (about 0.37ms per reading). It combines the density and intensity information to assess the severity of interference. The efficiency will be evaluated by extensive experiments in Section V.

IV. MUZI: MULTI-CHANNEL ZIGBEE NETWORKS

In this section, we will present the design and implementation of a multi-channel ZigBee protocol called MuZi(**Mu**lti-Channel **Zi**gBee) based on spatial locality of WiFi interference.

We assume that there are n sensor nodes distributed in the area and each node is equipped with omni-directional antenna. Each node transmits data to the sink directly or via multi-hop. Thus the entire network forms a tree topology rooted at the sink. There are M channels totally, which is 16 for IEEE 802.15.4. At any time, each node works at only one channel and is able to switch freely between M channels.

MuZi uses the proposed method in Section III for interference assessing and fixes the following problem induced by multi-channel in one network:

1) **Interference Detection.** A node needs to determine whether there exists interference around it and then take evasive action accordingly.

2) **Destination Channel Selection.** When finding the existence of interference, a node tends to switch to a relatively clearer channel. Moreover, in order to minimize the number of channels, we hope that all nodes in the same region share the same channel.

3) **Connectivity Maintenance.** Nodes that working at different channels can not communicate with each other directly. Therefore, some kind of coordination is needed to guarantee the connectivity between any node and the sink.

Fig. 1 illustrates the basic workflow of MuZi and the detailed implementation will be described in the following one by one.

A. Interference Detection

Using our method proposed in Subsection III.B, we can readily detect the presence of interference. The specific process is as follows:

1) Choose the threshold pair $<u_h, v_h>$. The choice of $<u_h, v_h>$ depends on the specific situation. In this paper, we set $<u_h, v_h>$ as <20%, -25dBm> empirically.

2) Assess the channel periodically and update $<u,v>$ pair.

3）After each update, comparing the current $<u,v>$ pair with $<u_h, v_h>$. If the current $<u,v>$ higher than $<u_h, v_h>$ (compare the first key at first and then the second key if the first key ties), interference is deemed as present; otherwise, interference is absent.

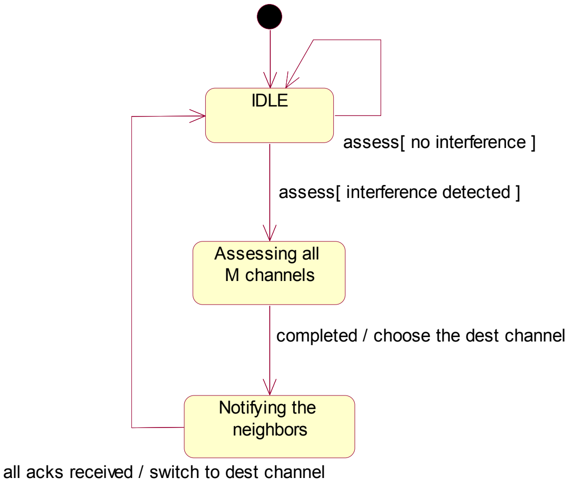


Fig.1. State Diagram

B. Destination Channel Selection

To minimize the channel number, a node needs to know the working channels of its neighbors. So each node maintains a channel table that taking $<Ngh, Ch>$ as a table entry, where Ngh and Ch denotes the node ID and its working channel respectively. After each switch, update the channel table.

With the channel table, destination channel selection algorithm works as follows:

1) Once interference is detected, it triggers the node re-assess all M available channels (for only one round) and get the newest $<u, v>$ pair for each channel. Choose the quietest channel *best*.

2) Search the channel table for the neighbor's best channel *nbrbest* which is similar to the *best*. (Note: Taking $<u_{delta}, v_{delta}>$ as a similar range, any channel within the scope $<u_{best}, v_{best}>$ to $<u_{best}+u_{delta}, v_{best}+v_{delta}>$ is viewed as similar) If *nbrbest* exists, set the final channel *dest* as *nbrbest*; otherwise, set *dest* as *best*. Similarly, the choice of $<u_{delta}, v_{delta}>$ depends on the specific situation. In this paper, we set $<u_{delta}, v_{delta}>$ as <5%, 10dBm> empirically.

C. Connectivity Maintenance

In the data collection service, it is a key issue to ensure the path connectivity between each node to the sink. This article assumes that the initial network deployment has formed a tree topology. Each node only needs to transmit its own data and forward data from its children to its parent. Therefore, to guarantee the connectivity in this service model, just ensure that each node is aware of its parent's working channel.

After each channel switch, the workflow of connectivity maintenance is as follows:

1) With the help of channel table, construct a reverse lookup table. Each table entry is <*Ch*, *Ngh1*, *Ngh2*,....>, denoting that *Nghi* is working at channel *Ch*.

2) Broadcast *dest* for each entry and wait a while to collect neighbors' acks. On the other side, after receiving the channel switch notification, each node sends ack back and updates its own channel table.

3) Switch to the new channel *dest* after all neighbors' acks are received.

Being aware of its parent's working channel, each node only needs to switch (if necessary) to the corresponding channel when it wants to transmit data.

V. PERFORMANCE EVALUATION

In this section, we will first evaluate the proposed interference assessment method on TelosB nodes and investigate whether it can efficiently distinguish between interference at different levels. Then, the performance improvement of MuZi is verified **on a testbed of 802.11 embedded nodes as interference sources and 802.15.4 TelosB motes** .

A. Performance of Interference Assessment

In this subsection, we conduct two different experiments to evaluate the performance of the proposed interference assessment method. The WiFi nodes used in this experiment are two embedded development board with Ubiquitous wireless NIC, one as the sender and another as the receiver. Both nodes work in 802.11g mode at 54Mbps. The sender generates a stream of UDP segments at different rates using the iperf tool. The ZigBee network consists of two TelosB motes equipped with 802.15.4-compliant TI CC2420 radios running TinyOS 2.1.

A.1 Efficiency of <u, v> Pair

The goal of the first experiments is to validate that our <u,v> pair is able to effectively distinguish between interference at different severity levels. Let d as the distance that 15.4 link from WiFi interference source and r as the WiFi interference rate, the experiments are divided into two groups: 1) d is fixed and r changes; 2) d changes and r is fixed.

A.1.1 Rate Changes

This experiment was done in the indoor environment which is the most likely to house overlapping 802.11 and 15.4 networks. We chose the unusual WiFi channel 4 to minimize external interference and ensured that only our WiFi devices were working at channel 4 during the experiments. At the same time, 15.4 network is operated at channel 15 that is at the center of WiFi channel 4. In these experiments, the receiver reads RSSI register per 10ms, and a total of 10,000 RSSI were collected for different WiFi interference rates.

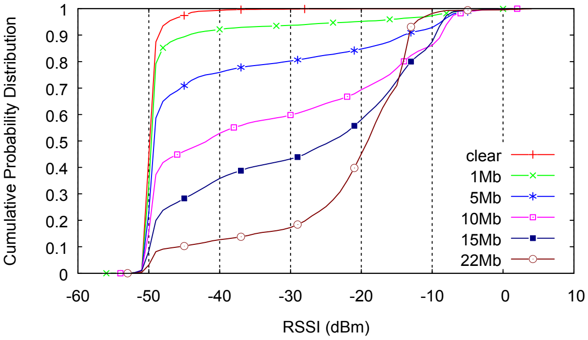


Fig.2. The CDF of RSSI under interference

Fig. 2 plots the cumulative probability distribution (CDF) of RSSI sensed by 802.15.4 receiver under different WiFi interference rates. From Fig.2, significant distinction between different interference could be easily observed. Especially, almost all (>95%) RSSIs are lower than -45 dBm in the absence of interference. So, setting the threshold H = -45 is an appropriate choice.

Different applications can set their own H as needed. The overall principle is to ensure significant distinction. From Fig. 2, too low or high H could lead to similar results and is hard to distinguish between different degrees of interference.

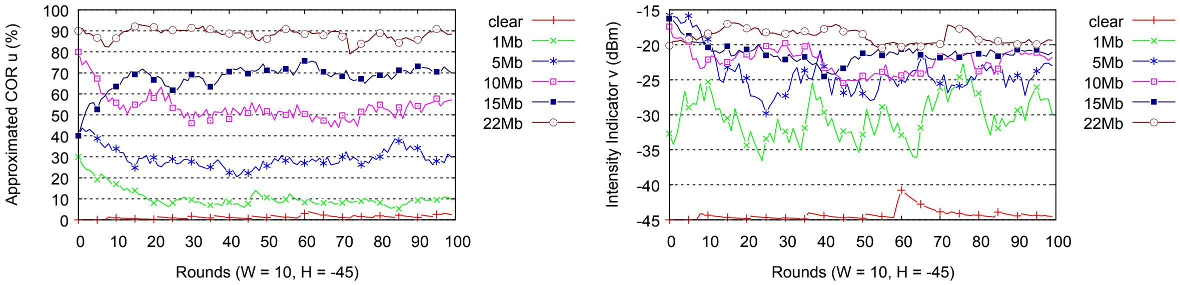
Let W=10 and H=-45, which means the <u, v> pair is calculated once per 10 RSSI readings. Fig. 3 illustrates the variance of <u, v> with the number of statistics increases. Note that when there is no RSSI higher than H in a round, set the current round v to H.

Fig. 3(a) shows that the approximated COR u is able to distinguish between interference at different rates easily and effectively. The same distance from WiFi source leads to the similar degree of interference intensity, so Fig. 3(b) does not show significant distinction.

A.1.2 Distance Changes

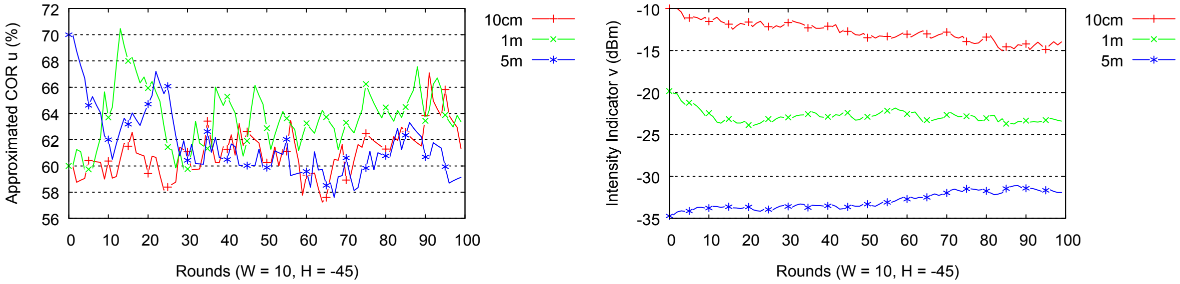
In this experiments, we fix the WiFi rate r close to half the channel capacity and change the interference distance d. Fig. 4 illustrates the variance of <u, v> with the number of statistics increases.

Due to the same interference rate, Fig. 4(a) shows the similar result and all estimates are between 60 and 70. Since W is set to 10, this means that there is at most one RSSI count difference between all rounds. Under the similar degree of interference denseness, it could be easily seen from Fig. 4(b) that the intensity indicator v is able to distinguish between interference at different distances easily.



(a) approximated COR *u* (b)Intersity Indicator

Fig.3 The indicator pair <*u*,*v*> under different WiFi Traffic



(a) approximated COR *u* (b)Intersity Indicator

Fig.4 The indicator pair <*u*,*v*> when the interference distance varies

A.2 Packet Loss Rate under Different Interference

In this experiment, we want to know the exact Packet Loss Rate (**PLR**) of 15.4 link under different interference and believe that disabling CCA helps us get the more realistic link performance.

This experiment has the same setup with the previous experiment, except that CCA is disabled in the 802.15.4 sender. The 15.4 sender transmitted a packet of 32 bytes (20 bytes payload and 12 bytes header) per 10ms and a total of 10,000 packets were transmitted. The PLR under different interference are filled in Table I and Table II.

TABLE I. THE IMPACT OF INTERFERENCE

WiFi Rate(bps)	PLR(%)
1M	6.20
5M	18.21
10M	32.42
15M	54.43
22M	81.80

TABLE II. THE IMPACT OF INTERFERENCE

WiFi Distance	PLR(%)
10 cm	31.99
1 m	10.93
5 m	6.59

Based on these extensive experiments, the following conclusion could be drawn easily: the higher the indicator pair <*u*, *v*> is, the more heavy interference is.

B. Performance of MuZi

The goal of the experiments is to evaluate the improvement of network performance when using MuZi compared with the single-channel network. The topology is shown in Fig.5, where 4 TelosB motes placed at the vertices of a 2.5m × 1m rectangle area and two WiFi sources placed in the link (0, 1) and (2, 3), respectively.

During the entire experiments, the left WiFi source operated at channel 4 and the right at channel 9. To minimize external interference, it's guaranteed that only our WiFi devices were working at channel 4 and 9 during the period of the experiments. Both WiFi sources generate a 500Kbps stream of UDP segments in 802.11g mode at 1Mbps using iperf tool as interference. At the interval of 60ms, a total of 10,000 15.4 packets were transmitted along the 0->1->2->3->0 loop each round.

We conducted a total of three experiments. In the first two rounds, all motes operated at channel 15 (overlapped with WiFi channel 4) and 20 (overlapped with WiFi channel 9) respectively. In the third one, to prevent MuZi from choosing the unoccupied channel such as 25 or 26, we limited the optional channel set as {15, 20}. Table II shows the result of all three rounds.

TABLE III. PERFORMANCE IMPROVEMENT OF MUZI

Service	Channel				Packets Received
	0	1	2	3	
Single	15				350
Single	20				2839
MuZi	15	15	20	20	9432

As can be seen from Table III, MuZi re-select channel 15 for node 0 and 1 and channel 20 for node 2 and 3. In this channel configuration with 4-hop communication, MuZi achieved 3.3 times throughput at least than the single-channel service.

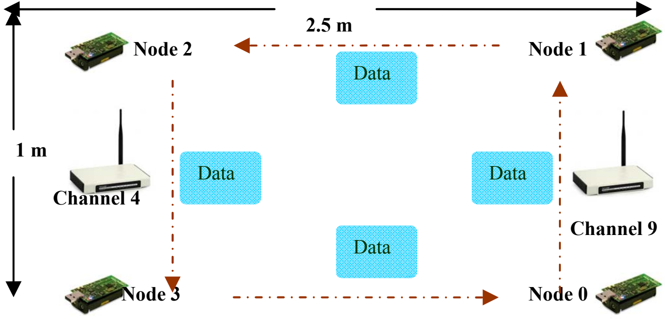


Fig 5 Experiment Topology Graph

VI. CONCLUSION

With more and more wireless system are deployed in CPS, the cross technology interference problem become a hot topic. This paper focuses on the interference avoidance of ZigBee from WiFi networks and analyzes in theory the limitations of the existing interference assessment model based on SINR. Further, an approach jointly considering the degree of intensity and denseness is proposed to overcome the inherent limitations of the model. Through experiments, we show that our method is able to effectively distinguish between interference at different severity levels. Based on the method, we design the MuZi protocol that augments multi-channel mechanism for ZigBee networks. Different from the existing work, MuZi considers the locality of interference in time and space. We also present the solution induced by multi-channel mechanism in one network. Our extensive experiments on a testbed of 802.11 embedded nodes and 802.15.4 TelosB motes show that, under the existence of WiFi interference, MuZi can achieve 3.3 times throughput than the traditional single-channel method.

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