Exploiting Temporal and Spatial Variation for WiFi Interference Avoidance in ZigBee Networks

Gaotao Shi*

School of Computer Science and Technology, Tianjin University and
Tianjin Key Laboratory of Cognitive Computing and Application,
Tianjin, 300072, China
Email: shgt@tju.edu.cn
*Corresponding author

Ruitao Xu

School of Computer Science and Technology, Tianjin University
Tianjin, 300072, China
Email: xrtgavin@163.com

Yantai Shu

School of Computer Science and Technology, Tianjin University
Tianjin, 300072, China
Email: ytshu@tju.edu.cn

Jun Luo

School of Computer Engineering, Nanyang Technological University
Singapore 639798
Email: junluo@ntu.edu.sg

Abstract: In the Internet of Things (IoT), different wireless technologies will be used to build various micro-systems, which result mutual interference among these micro-systems. Specifically, ZigBee networks share the 2.4GHz ISM band with WiFi but have much lower transmission power. Therefore, the ZigBee networks inevitably suffer the interference from WiFi Networks. Unlike previous approaches that focused on minimizing effect on link level, this paper focuses on utilizing the temporal and spatial feature of WiFi interference to adjust Zigbee channel over the whole networks. In this paper, we first experimentally examine the spatio-temporal variation. Then we present a novel interference assessing method. This proposed method jointly considers the intensity and density of WiFi interference in order to better characterize the relation between interference and link quality. Further focusing on the interference locality, we propose MuZi (Multi-channel ZigBee) as an interference avoiding approach for ZigBee networks. MuZi consists of three components: interference assessment, channel switch, and connectivity maintenance. It aims to determine a better working channel for each node while taking network connectivity into consideration. 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.

Keywords: ubiquitous sensing, ZigBee, spatio-temporal variation, multi-channel, interference avoidance

Biographical notes: Gaotao Shi received the Ph.D. degree from Harbin Institute of Technology, Harbin, Heilongjiang, China, in November 2006. He joined School of Computer Science and Technology, Tianjin University, Tianjin, China in December 2006. He was an Assistant Professor from December 2006 to June 2011. He is currently an associate Professor with Tianjin University since July 2011. His research interests include wireless sensor networks and embedded network system.

Ruitao Xu received the B.Sc. and M.S. degree in computer science in 2009 and 2011 respectively from Tianjin University, Tianjin, China. His research interests are wireless sensor networks.

Yantai Shu is currently a Professor with Tianjin University. He received the Chinese equivalent to the BS, MS, and PhD degrees in electronics engineering from Tianjin University. He is serving as vice president of the university from 1993-1997. His current interests are focused on computer

communication networks, wireless networks, real-time systems, modelling, and simulation.

Jun Luo received the Ph.D. degree in computer science from the Swiss Federal Institute of Technology in Lausanne (EPFL), Lausanne, Switzerland, in 2006. From 2006 to 2008, he has worked as a Post-Doctoral Research Fellow with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. In 2008, he joined the faculty of the School of Computer Engineering, Nanyang Technological University, Singapore, where he is currently an Assistant Professor. His research interests include wireless networking, mobile and pervasive computing, distributed systems, multimedia protocols, network modeling and performance analysis, applied operations research, as well as network security.

1. Introduction

Recently, the IoT (Internet of Things) has drawn increasing attentions [Gershenfeld, Krikorian and Cohen 2004] because it aims at enabling a deep and comprehensive integration of human-world and physical-world. In these systems, various wireless communication technologies have been witnessed, such as WiFi, ZigBee and Bluetooth [Chipara et al. 2010 and Shi et al. 2009] for ubiquitous sensing and data collection. 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 results 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 (e.g., a shorter back off time slot), ZigBee is affected more severely by WiFi networks. With the growing popularity of WiFi deployments, the situation will get even worse. Consequently, how to improve communication performance of ZigBee under the existence of WiFi interference is becoming a crucial issue.

There have been some studies about how to avoid WiFi interference in ZigBee network [Ko et al 2009 and Hauer et al. 2009]. The most direct way to mitigate such interference for the ZigBee network is to avoid the channels occupied by WiFi. There are mainly two schemes to achieve interference avoidance by channel assignment. The first is global channel assignment, in which all sensor nodes share the same channel (planed or not planed) to communicate with each other. However, this scheme has a fatal drawback that some of the local areas may suffer severe degraded performance due to the spatial locality of WiFi interference, thereby degrading the entire network performance. Moreover, with the increasing WiFi deployments, it is almost impossible to find the globally unoccupied channel. The second scheme is local channel assignment in which different nodes in a sensor network, or the same node over different time, will use different channels to avoid interference from nearby WiFi sources. Intuitively, the interference in different space over time is different. The experiment in section 3 of this paper also verifies this intuition. Therefore, the later scheme complies with the locality of WiFi deployment naturally and will have a better performance to avoid the interference.

Built on our previous work [Xu et al. 2011], this paper proposes a local interference avoidance protocol called MuZi. Unlike previous approaches that focused on minimizing effect on link level, this paper focuses on utilizing the temporal and spatial feature of WiFi interference to adjust Zigbee working channel over the whole networks. Following the way, MuZi augments each node with channel switching capability to choose the cleanest channel dynamically for data communication. In detail, our paper makes the following contributions:

1) We experimentally measure the feature of interference over space and time. It demonstrates that the interference is varying in space and in time, and it thus motivate us to utilize the multi-channel mechanism for interference avoidance.

2) We present a novel method for assessing the severity of WiFi interference. Contrary to the current solution, the proposed method jointly considers the intensity and density of WiFi interference and thus can represent the impact of WiFi interference on the link performance of 15.4 more accurately.

3) We further propose MuZi as an interference avoidance protocol, based on the multi-channel capability of ZigBee radios. Using the proposed interference assessment method, ZigBee nodes assess the severity of the local interference that they are suffering and then choose a new working channel with lower interference if necessary.

4) We present the detailed implementation of MuZi in TinyOS[1] and make extensive experiments on a testbed of WiFi embedded nodes and ZigBee TelosB[2] motes. The 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 2. Section 3 introduces the ZigBee specification and experimentally examines variation feature of interference over time and space. Section 4 discusses the limitations of the traditional PRR-SINR (Packet Reception Rate and Signal to Interference-plus-Noise Ratio) model and introduces a new interference

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[1] TinyOS is an open-source operating system designed for wireless embedded sensor networks.

[2] TelosB mote is an open source platform designed to enable cutting-edge experimentation for the research community.

assessment method. Section 5 presents the detailed design of MuZi. Section 6 reports the implementation of MuZi in TinyOS and its evaluation in our testbed. Section 7 concludes this paper.

2. Related Work

The WSN community has now acknowledged the impact of WiFi interference on WSN applications in various settings. The works in the first category focus on the mechanism or principle of interference. An empirical results was found in [Ko et al 2009] in a hospital setting. The results show that running CTP [Gnawali et al. 2009] on a ZigBee network that overlapped with an active 802.11 channel decreased the end to end goodput by a factor of three. The impact of WiFi interference on ZigBee networks was studied in [Hauer et al. 2009] and the authors found that the position distribution of bit errors in ZigBee packets is temporally correlated with WiFi traffic. The authors in [Yoon et al. 2006] found that ZigBee packet loss as high as 87%, with an WiFi sender located in between two ZigBee nodes five meters apart.

Currently, there exist some works trying to predict ZigBee link performance based on SINR (Signal to Interference plus Noise Ratio) under the existence of WiFi sources. For example, a passive interference measurement method based on the PRR-SINR (Packet Reception Ratio-SINR) model is proposed in [Liu et al. 2010]. However, performance prediction model solely based on SINR is inaccurate. In general, PRR-SINR model is only suitable to predict link performance in the static environment, not for a real dynamic environment, because SINR and the conflict time ratio are both instantaneous values and vary over time. At the same time 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 cannot tell whether the signal is from sender or from interference source.

A reasonable approach for ZigBee networks to mitigate WiFi interference is to switch the network to channels that do not overlap with an active WiFi channel. According to ZigBee 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 cannot avoid the interference from WiFi hotspots which varies in different space over different time. In [Hodgdon 2003], AFH (Adaptive Frequency Hopping) is proposed for coexistence between Bluetooth and WiFi, which is similar with the design in MuZi with different solutions. This work eliminates the bad frequencies and uses the left good frequencies as the future hoping sequences. But the final hoping scheme is also a pseudo-random way like that in the original Bluetooth. In [Musaloiu-E. and Terzis. 2007], the authors proposed a distributed channel selection mechanism that detects 802.11 interference using periodic RSSI (Received Signal Strength Indicator) samples. However, these works did not consider the locality of interference and thus cannot provide a satisfactory link performance. Moreover, static channel assignment may not

work as planned due to nodes 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 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 ZigBee and WiFi 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 finding, the authors in [Huang et al. 2010] 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. The idea is neat but the self-similarity feature appears to be restricted to only describe the WiFi interference in 2.4GHz, hence the method can work only when pure WiFi traffic exists. At the same time the solution does not consider the locality of interference. For example, for two pairs of ZigBee communication links that are geographically separated, the white space may not happen at the same time. Applying the same interference model to them can hinder protocol efficiency.

The interference pattern between ZigBee and WiFi networks is examined in [Liang et al. 2010] at bit-level granularity and the authors find that the bit-error distribution is related with the distance of interference from WiFi. Based on this finding, they designed a BuzzBuzz protocol to mitigate WiFi interference through header and payload redundancy. This method is very direct in the design philosophy but it is not compatible to the ZigBee specification. Different with this work, the proposed MuZi aims to support coexistence with legacy ZigBee specification.

Channel diversity is studied in [Doddavenkatappa et al. 2011] where the authors found that when the link quality of a channel is bad, it is highly likely that a good channel can still be found and its quality will remain good for at least a few minutes. And they also proposed a protocol to exploit the channel diversity using packet reception ratios as metrics. This paper provided evidences for our work in that there is a high probability to find a better channel if the current working channel is suffering interference. However, this work does not consider the feature of interference and the accurate interference assessment.

Besides above works, [Zhang and Shin 2011] and [Wang et al. 2011] propose to use faked competing signal to cheat the WiFi nodes so that the protected ZigBee networks could have the chances to occupy channel. In [Zhang and Shin 2011], a mechanism CBT (Cooperative Busy Tone) is proposed to improve the visibility of ZigBee devices to WiFi. In this mechanism, a busy tone is scheduled concurrently with the desired transmission by a separate

ZigBee node. In [Wang et al. 2011], the authors proposed to send WiFi compliant signals to refrain WiFi stations from transmitting. This method exploits the WiFi CCA (Clear Channel Assessment) mechanisms but needs to modify PHY Header and induces a dedicated policing node which adds the system cost.

3. Spatial-temporal Variation of Interference in ZigBee Networks

This section aims to show the characteristics of interference suffered by the ZigBee networks. We first give a simple overview of the ZigBee specification standard to show its drawback when facing the cross-technology interference. Then we demonstrate the real measurement results that the interference varies in different location over different time. Also because when one channel is occupied by WiFi, other channels of ZigBee are free with high probability [Doddavenkatappa, et al. 2011]. All these facts jointly motivate the design of MuZi.

3.1 ZigBee Specification

ZigBee is currently the de facto standard for wireless sensor networks. It supports 16 non-overlapping channels (usually referred by numbers 11 through 26) and these channels are defined in the 2.4 GHz ISM band with each channel occupying a bandwidth of 2 MHz and an inter-channel separation of 3 MHz.

For constructing a ZigBee mesh network, a node is assigned as the coordinator who is responsible for determining the working channel. The channel selection process is commonly done by scanning the signal energy over all the channels to find the quietest one. Then all other sensors will also work in this selected channel. Consequently, all the nodes have to work with the only channel which is locally quietest only for the coordinator.

However, if each node can switch its working channel to a cleaner one, the network will have a better performance for data transmission. The widely used ZigBee radios have a quick channel switch capabilities. For example, the CC2420 transceiver in sensor networks and the more recent CC2500 have channel switching times of only 300 microseconds and 90 microseconds respectively [Wang et al. 2011]. Such an overhead is negligible when compared to the 4 milliseconds required to transmit a maximum sized packet (of 128 bytes).

3.2 Temporal and Spatial Variation of Interference

Here we first present a definition which will be frequently referred for easily explaining the main idea of our method. We define the channel occupancy rate (COR) as the TIME proportion occupied by the interference signal when no ZigBee frames are transmitting. The COR is similar to the conflict time ratio, but could be easily approximated. Thus, COR can be taken as an indicator of interference density.
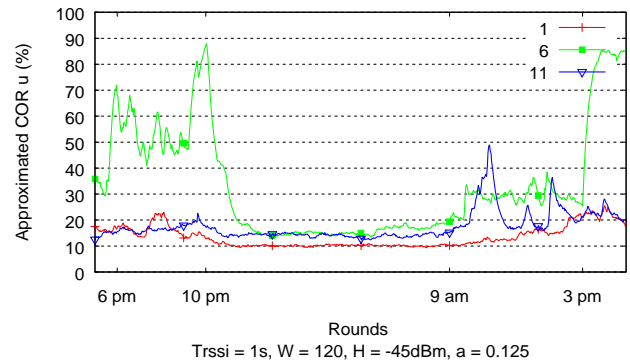

Figure.1. Temporal Feature of Interference

In order to understand the features of interference, we conducted experiments to investigate the temporal and spatial variation over different time in different space. To this end, we firstly used a TelosB mote randomly placed in our lab building to collect the trace of COR over time. The collected RSSIs[3] are used to estimate the COR which shows the amount of variation. The results are plotted in Figure.1 from which we can see the interference in different channels varies with different time. Specifically, the interference in channel 6 from 6pm to 10:30pm is stronger than that from 11pm to 9:30am. This is because the staffs and students were absent from the lab between 11pm and 9:30am, which leads to a light WiFi traffic. Thus the predefined working channel cannot adapt with the interference if the node does not change its working channel during the whole lifetime.

Furthermore, we collect the data in three different places at the same time to investigate the interference variation with space. The results are plotted in Figure.2. The parameters used in experiments can be found in section 4 and 5. The interferences in three commonly used WiFi channel 1, 6 and 11 exhibit different features. In detail, in place A, the interference in channel 11 is strongest among them and in place B, the interference behaviors almost in the same level. In place C, however, the strongest interference happens in channel 6. This experiment shows that the interferences are different for different places and thus the nodes in different places should work with different channels.

4. A Simple Method for Interference Assessment

In order to avoid the interference, we need an efficient mechanism to judge whether a node is suffering the interference and how serious it is. In this section, we will analyze the limitation of PRR-SINR model and then a lightweight method for accurately assessing WiFi interference is proposed. This assessing method takes the intensity and density of interference into account to overcome the limitation of PRR-SINR model.

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[3] In TelosB motes, the RSSI can be obtained by reading a specific register even there are no ZigBee frame transmissions.

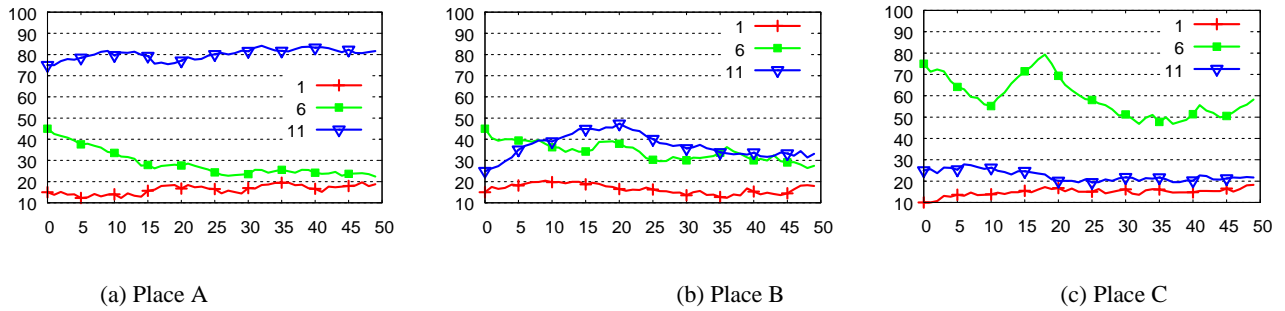(a) Place A   (b) Place B   (c) Place C

Figure.2. Spatial Variation of Interference $T_{rssi} = 100$ ms $W = 20$ $H = -45$ dBm

4.1 Limitation of PRR-SINR Model

Currently, under the existence of WiFi sources, the PRR-SINR [9] model is the most commonly used to predict packet reception rate of ZigBee 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 PRR (packet reception rate) for example, to briefly explain how to obtain the PRR gradually from BER(Bit Error Rate)[Liu et al. 2010].

In ZigBee specification, 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 [Sklar 1995], the BER, denoted as P_B, can be expressed as

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

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 WiFi nodes and ZigBee nodes send data at the same time. If the distances of the sender and WiFi sources from the receiver are all known in advance, we can estimate the SINR when conflict happens based on the existing wireless signal attenuation model. However, conflict does not always happen. Therefore, the conflict time ratio needs to be estimated to calculate the PRR. Assuming that WiFi nodes and ZigBee nodes 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 the average packet length in ZigBee

networks is L bytes, we can further compute PER (packet error rate) 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 inaccurate.

4.2 The Proposed Assessment Method

Our interference assessing method is based on the common sense that interference involves not only interference intensity but also interference 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 have the severity of interference be assessed accurately. In addition to 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.

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 other wireless networks, and we choose the average of these RSSIs greater than H as the intensity indicator. Based on the analysis, algorithm 1 describes the detailed method for determining whether the interference exists or not.

This algorithm takes H as the threshold and finally calculates the $<u,v>$ indictor pair. It samples RSSI reading

on its current channel periodically and collects W RSSI readings in each round (Line 3). Based on the RSSI set, the number of RSSI samples that bigger than H can be calculated out as well as the average value of these RSSIs (also beyond H) (Line 5). And then the final indicator pair $<u,v>$ is taken as $<N/W, A/N>$ (Line 7), where N/W is used to approximate COR and A/N as the intensity indicator.

Algorithm 1. Calculate_$<u,v>$

Input: Channel i;
Output: Interference pairs $<u,v>$
1   $S \leftarrow \Phi$, $N \leftarrow 0$, $A \leftarrow 0$;
2   **repeat**
3   sample RSSI reading s_i on channel i;
4     $S \leftarrow \{s_i\}$;
5   **if** $s_i > H$, **then** $N++$, $A \leftarrow A + s_i$;
6   **until** $|S| = = W$
7   $u \leftarrow N/W$, $v \leftarrow A/N$;

Our method meets the required features for lightweight interference detection in low-cost sensor networks. 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. *More importantly, the method does not differentiate the interference traffic and takes all interference sources as uniform signal strength and thus is efficient especially when multiplex complex interference sources exist.* The efficiency will be evaluated by extensive experiments in Section 6.

5. MuZi: Multi-Channel ZigBee Networks

In this section, we will present the design of MuZi (Multi-Channel ZigBee) based on spatial locality of WiFi interference. We set out with the explicit goals of not requiring custom hardware and supporting coexistence with legacy ZigBee specification.

5.1 Overview of MuZi

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 ZigBee networks. At any time, each node works in only one channel and is able to switch freely between M channels. Figure.3 is the common state diagram for sensor nodes when MuZi operates.

MuZi consists of three components: interference assessment, channel switch, and connectivity maintenance. The **interference detection** component is used to determine whether the interference exists around a node. MuZi uses the proposed method introduced in Section 4 to assess the interference. If the interference is detected, the **channel switch** component will be triggered to switch to a relatively clearer channel. Moreover, in order to minimize the number of channels, the process of channel selection tries to assure that all nodes in the same region share the same channel as possible as it can. Finally, the **connectivity maintenance** component is needed to guarantee the connectivity between any node and the sink. In the following subsections, these processes will be introduced in detail.
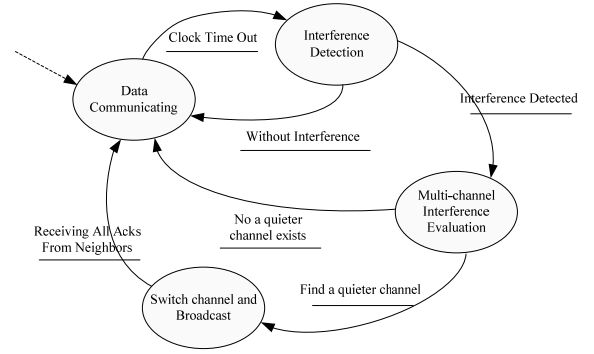

Figure. 3. Nodes State Diagram of MuZi

5.2 Interference Detection

Using our method proposed in Subsection 4.2, we can readily detect the interference and assess the severity. Note that the $<u, v>$ pair obtained from Algorithm 1 only represents the interference information for one round. However, the interference might vary over time. In order to reflect the interference situation truthfully and respond to the variation quickly, we employ exponentially weighted moving average (EWMA) technology which is used by wired network to estimate round-trip time. In this way, u and v is processed respectively according to the following rule when algorithm 1 finishes:

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

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

Algorithm 2. Interference detection

Input: Threshold $<u_h, v_h>$;
Output: TRUE if interference detected; otherwise FALSE;
1   X_1 and X_2 are initiated once the channel has been switched;
2   On detection clock timeout
3   **call** Algorithm 1 to obtain the $<u, v>$ pair;
4     $X_1 \leftarrow (1-\alpha)*X_1 + \alpha*u$;
5     $X_2 \leftarrow (1-\alpha)*X_2 + \alpha*v$;
6   **if** $<X_1, X_2>$ is bigger than $<<u_h, v_h>$
7   **return TRUE;**
8   **else return FALSE;**

The detailed interference detecting process is presented algorithm 2. The algorithm choose a threshold pair $<u_h, v_h>$ as the interference reference which depends on the specific situation. In this paper, we set $<u_h, v_h>$ as $<20\%, -25dBm>$ empirically. Then the channel will be checked periodically and $<u,v>$ pair is updated at the end of every round (Line 3). After each update, the current $<u,v>$ pair is compare with $<u_h, v_h>$ and 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) (Line 6), the interference is deemed to be presented.

5.3 Destination Channel Selection

When the interference is detected by a node, it is likely to switch to a much cleaner channel. Generally speaking, the interference will be minimized over the network if each node works with the cleanest channel. However, with different working channels, the nodes will not be able to communicate with each other. This will result in several "isolated island" in the networks. Therefore, there exists a tradeoff between the interference avoidance and the number of working channels.

Fortunately, we have illustrated in section 3 that the interference has the locality in space. This means that the nodes located closely will be exposed to the similar interference level and will have the opportunity to own the same working channels. MuZi controls these nodes to select the same channel as possible as it can.

To do that, a node needs to know the working channels of its neighbors. So each node maintains a ***Neighbor-Channel table*** taking *<Ngh, Ch>* as a table entry, where *Ngh* and *Ch* denote the node ID and its current working channel respectively. After each channel switching, the channel table will be updated responsively. With the channel table, destination channel selection algorithm works as illustrated in Algorithm 3. Once interference is detected, the nodes are triggered to re-assess all *M* available channels (for only one round) (From Line 1 to Line 8) and obtain the newest *<u, v>* indicator pair for each channel. At the end of the algorithm, the nodes will choose the quietest channel CH_{best} as the candidate working channel (From Line 9 to Line 12).

Algorithm 3. Select the better channel

Input: NULL;
Output: the better next working channel CH_{dest};
1   On detecting interference using algorithm 2;
2      $u_{best} \leftarrow \infty$, $v_{best} \leftarrow \infty$;
3   **For** each channel CH_i;
4   run Algorithm 1 to get the $<u_i,v_i>$ pair;
5   **if** $<u_{best}, v_{best}>$ is bigger than $<u_i,v_i>$
6            $u_{best} \leftarrow u_i$, $v_{best} \leftarrow v_i$;
7            $CH_{best} \leftarrow CH_i$;
8      $CH_{dest} \leftarrow CH_{best}$;
9   **For** each channel CH*i* in channel tabel
10   **If** the $<u_i, v_i>$ is more close to $<u_{best} \pm u_{delta},$
                $v_{best} \pm v_{delta}>$
11            $CH_{dest} \leftarrow CH_i$;
12   **return** CH_{dest}

In order to decrease the number of channels, the algorithm will search the channel to determine a channel which is used by one or several neighbors and with the closest interference level to the CH_{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 the closeness) If the channel is found, set it as the final destination channel CH_{dest}; otherwise, set CH_{best} as the final destination channel. Similarly, the choice of $<u_{delta}, v_{delta}>$ depends on the specific situation or the application demand. In this paper, we set $<u_{delta}, v_{delta}>$ as $<5\%, 10dBm>$ empirically.

5.4 Connectivity Maintenance

After the nodes switch channel semi-dependently, some nodes working with the same channel previously could not communicate with each other anymore because the new channel may be different between these two neighbors. In the data collection service, it is a key issue to ensure the path connectivity between each node to the sink. This paper assumes that the sensor networks have formed a tree topology during the initial network deployment. Each node only needs to transmit its own data or forward its children's data to its parent. Therefore, to guarantee the connectivity in this service model, each node needs to be aware of its parent's working channel.

In order to keep the network connectivity, MuZi construct a ***Channel- Neighbor table*** which is a reverse lookup table of ***Neighbor-Channel table***. Each table entry in ***Channel- Neighbor table*** follows the format *<Ch, Ngh1, Ngh2,....>*, where *Nghi* is denoted as a neighbor with working channel *Ch*. The workflow of connectivity maintenance in MuZi is illustrated in Algorithm 4.

Algorithm 4. Connectivity maintaining

Input: Channel Tabel, CH_{dest};
Output: NULL;
1   for each entry *<Nghi, Ch_k>* in ***Neighbor-Channel table***
2.   insert *Nghi* into the ***Channel- Neighbor table*** corresponsive to Ch_k;
3   for each entry *<Ch_k, Ngh1, Ngh2,....>* in ***Channel-Neighbor table***
4   Broadcast (CH_{dest}) using channel Ch_k;
5   waiting for the acks from all the neighbors in the current entry;
6   switch to the new working channel CH_{dest};
7   On receiving the Broadcast message from its neighbors
8   update ***Neighbor-Channel table***;
9   send an ACK;

For each entry, the node broadcasts to all the neighbors the information about the future working channel CH_{dest} on the neighbor's channel (Line 4) and waits for a while to collect neighbors' acks (Line 5). After all neighbors' acks are received, the node switches to the new channel CH_{dest} (Line 6). As such, when the node receives the broadcast message from one neighbor, it also sends back an ack and updates the ***Neighbor-Channel table*** (From Line 7 to Line 9). In this way, each node is aware of its parent's working channel and just switches (if necessary) to the corresponding channel when it wants to transmit data to the sink.

5.5 Summary of Channel Handoff in MuZi

In this subsection, we like to summarize the channel handoff procedure when nodes run MuZi. This procedure is illustrated in Figure. 4 where the segments with arrow denote the RSSI samples. Each node will periodically assess the interference in its current working channel and on detecting interference searches a relatively clear channel as the new working channel.
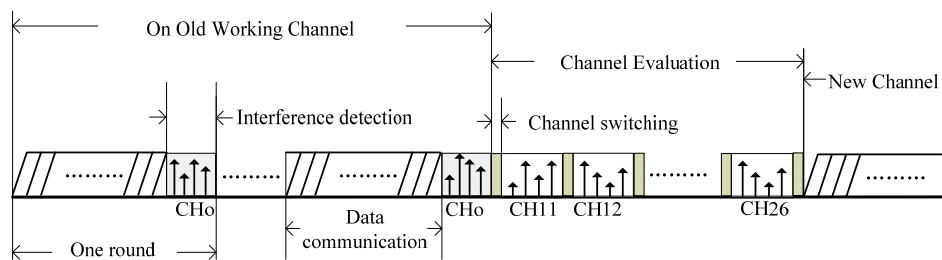
Figure.4. Channel Handoff Procedure in MuZi

```
interface MultiChannelEvaluator {
    command error_t eval ();  // request to evaluate all //channels in one shot
    event void evaluatDone(error_t error, uint8_t destChannel);  // signal in response to a request
}

interface State {
    // This will allow a state change so long as the current //state is S_IDLE.
    async command error_t requestState(uint8_t reqState);//Force the state machine to go into a certain
                                        // state,regardless of the current state it's in.
    async command void forceState(uint8_t reqState);     // Set the current state back to S_IDLE
    async command void toIdle();
    async command bool isIdle();
    async command bool isState(uint8_t myState);// Get the current state
    async command uint8_t getState();
}
```

Figure 6 main interfaces in MuZi

6. Implementation and Experiments

In this section, we will describe our implementation of MuZi in TinyOS operating system and evaluate the proposed interference assessment method on TelosB nodes to investigate whether it can efficiently distinguish between interference at different interference levels. The performance improvement of MuZi is also verified on a testbed of WiFi embedded nodes as interference sources and TelosB motes. Note: although the evaluation is performed under WiFi interference, our solution works well under others interference in 2.4GHz.

6.1 Implementation of MuZi

In this subsection, the detailed implementation of MuZi in TinyOS is presented. TinyOS is an open-source operating system designed for wireless embedded sensor networks. It features a component-based architecture enables rapid development while minimizing code size. Our implementation of MuZi is built on top of the standard component AMSender Media Access Control of TinyOS. Thus, the interference-aware applications running with MuZi must explicitly use the interface provided by MuZi. The software architecture of MuZi is illustrated in Figure. 5.

In order to implement channel evaluation, we use two independent components: Periodic Channel Evaluator (PCE) and Multi-Channel Evaluator (MCE). These two components run as daemon applications. PCE periodically checks the quality of current working channel and if it finds that the interference level is beyond a predefined threshold,

it will transfer the control to MCE which will check the interference level in all sixteen channels in one shot and finally select the quietest channel. The function is done by MultiChannelEvaluator interface in figure 6.
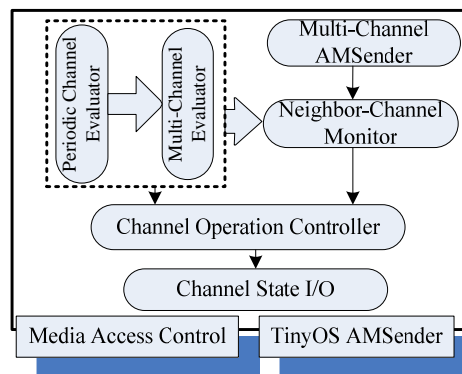

Figure. 5. Software Architecture of MuZi

The MCE is used to scan each channel to check the interference level and thus needs to need change the working channel in a very short time. As a result, channel operation will bring negative effect on common sending and receiving if the operation cannot be properly scheduled. In the implementation of MuZi, we take the channel as a shared resource and provide a mutually exclusive mechanism. The function is provided in Channel Operation Controller (COC) component and its states include IDLE and ACQUIRED which is claimed in component Channel State I/O.

6.2. Efficiency of <u, v> and Interference Assessment

In this subsection, we conduct two different experiments to evaluate the efficiency of <u, v> pairs and the performance of the proposed assessment method. The WiFi nodes used in this experiment are two embedded nodes 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 ZigBee-compliant TI CC2420 radios running TinyOS 2.1.

The goal of the first experiment is to validate that our <u, v> pair is able to effectively distinguish between interferences at different severity levels. Let d as the distance between ZigBee link and 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.

We firstly examine the effect of data rate when the distance is fixed. This experiment was done in the indoor environment which is the most likely to house overlapping WiFi and ZigBee 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, ZigBee 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.

Figure. 7 plots the cumulative probability distribution (CDF) of RSSI sensed by ZigBee receiver under different WiFi interference rates. From Figure.7, significant distinction between different interferences could be easily observed. Especially, almost all (>95%) RSSIs are lower than -45 dBm in the absence of interference. Therefore, 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 Figure. 7, too low or too 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. Figure. 8 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. Figure. 8(a) shows that the approximated COR u is able to distinguish between interferences at different rates easily and effectively. The same distance from WiFi source leads to the similar degree of interference intensity, so Figure. 8(b) does not show significant distinction.
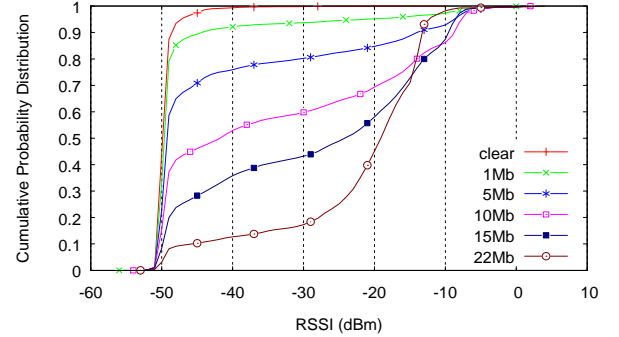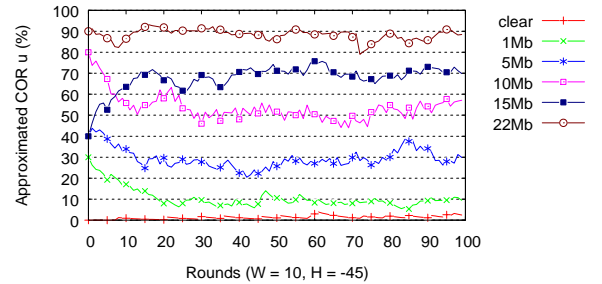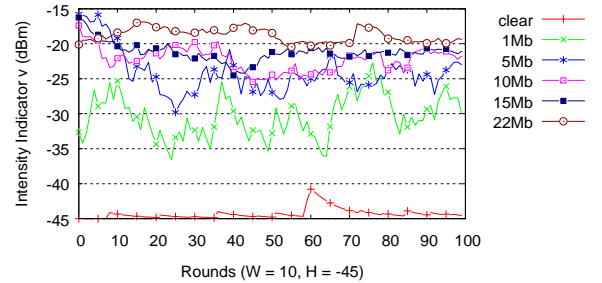

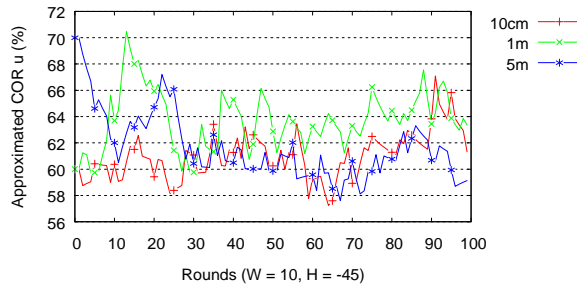Figure.7. The CDF of RSSI under different interference

(a) approximated COR u

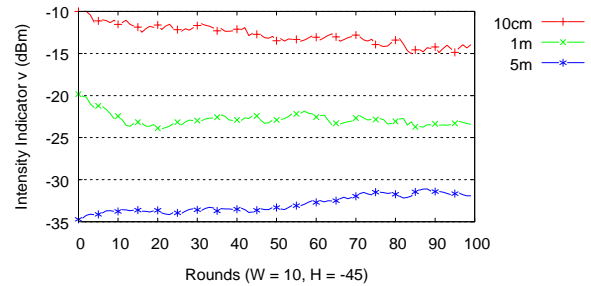

(b) intersity indicator

Figure.8 The indicator pair <u,v> under different WiFi traffic

(a) approximated COR u

(b) intensity indicator v.

Figure.9 The indicator pair <u, v> when the interference distance varies
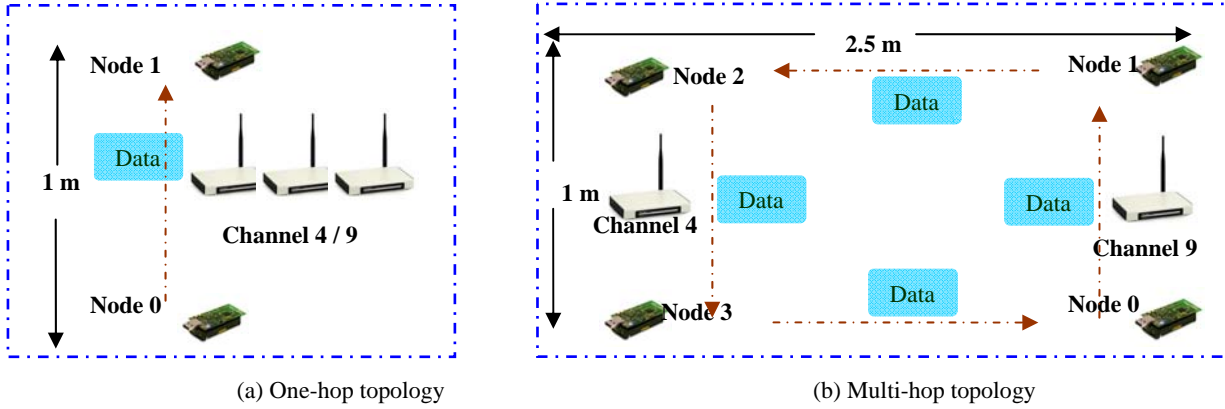
(a) One-hop topology   (b) Multi-hop topology

Figure. 10. two experiment topologies

Then we fix the WiFi rate *r* close to half the channel capacity and change the interference distance d. Figure. 9 illustrates the variance of <*u*, *v*> with the number of statistics increases. Under the same interference, Figure. 9(a) shows the similar results and all estimates are between 60 and 70. *W* being set to 10 means that there is at most one RSSI count difference between all rounds. Under the similar severity of interference, it could be easily seen from Figure. 8(b) that the intensity indicator *v* is able to easily distinguish the interference at different distances. These experiments show that the higher the indicator pair <*u*, *v*> is, the more heavy interference is.
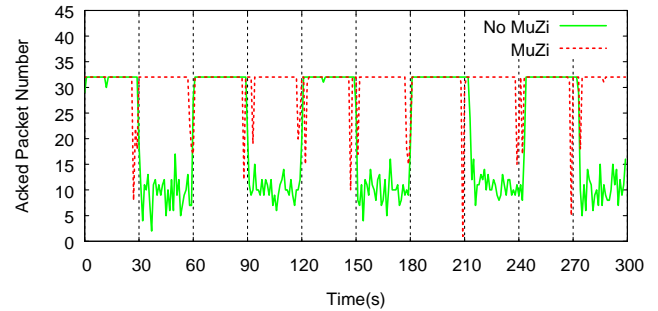
6.3. One-hop Performance of MuZi

The goal of the experiments is to evaluate the improvement of network performance when using MuZi compared with using the single-channel network. The experiments are done under two different topologies namely one-hop topology and multi-topology, which are shown in Figure.10.

In the one-hop topology, illustrated in Figure 10(a), three WiFi nodes as interference sources are placed among two TelosB motes. These three WiFi nodes work with 802.11g model with physical rate 1Mbps. Among them two WiFi nodes work as iperf servers in channel 4 and 9 alternatively. The third node sends the data with rate 500Kbps using an iperf data flow as the interference traffic and changes its working channel every 30s between channel 4 and channel 9. At the same time, the CSMA mechanism in TelosB node 0 is turned off and send the data with packet length 32B every 32ms.

We collected the data in the receiving node and plotted the results in Figure.11. Figure.11 (a) shows the number of data sent out successfully from node 0 during the experiments under two kinds of different protocol configurations. From Figure.11 (a) we can easily find that when the node runs MuZi, the number of data received is always kept at a high level except when the channel is being changed at every 30s. However, if the node is not configured with MuZi, the amount of received data will be reduced to very low level when the interference channel is coincided with the TelosB nodes. This shows that our MuZi

protocol is able to avoid the interference efficiently by automatically changing the working channel.

Figure.11. (b) further plots the difference of received data in these two scenarios. The data is derived from Figure.11 (a) by calculating the difference of the number of received packets. The red curve shows the gain when using MuZi compared with that without MuZi and the green curve shows the loss when using MuZi due to the channel adjust. The packet loss in a very short time when using MuZi is caused by channel assessment and selection in MuZi triggered by the variation of interference during the WiFi channel switching. It is clearly seen that the link quality is greatly improved when running MuZi.

(a) The number of successfully sent out in Node 0
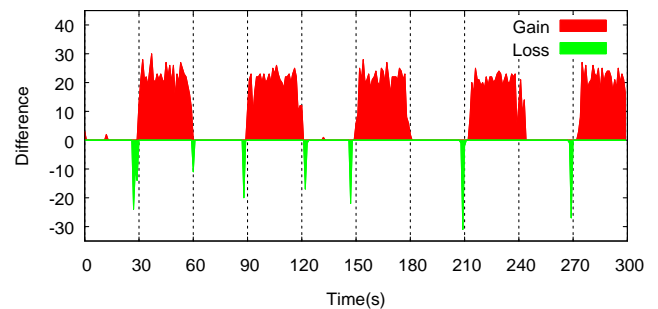
(b) Difference of the data amount

Figure. 11. one-hop experiment results

6.4 Multi-hop topology experiments

We further investigate the MuZi performance under multi-hop topology which is illustrated in Figure.10 (b) 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 packets from 802.15.4 node were transmitted along the 0->1->2->3->0 loop each round.

Table 1. Performance Improvement of MuZi

Exp No.	Service	Channel				Packets Received
		0	1	2	3	
#1	Single	15				350
#2	Single	20				2839
#3	MuZi	15	15	20	20	9908

We conducted a total of three experiments. In the first two experiments, all motes were 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 1 shows the result of all three rounds.

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

We further count the number of received data in each node to analysize the reason of the bad performance for single channel experiment #1. Table 2 lists the number of received packets. From the table we can see that in experiment #1, the performance of links node 1-> node 2 and node 3-> node 0 were degraded severely. However, in experiment #2, these links were not affected by the external interference.

Table 2. The number of received packets in each experiment

Exp. #1		Exp. #2		Exp. #3	
Node	Packets Received	Node	Packets Received	Node	Packets Received
#1	9997	#1	9999	#1	9997
#2	3823	#2	9996	#2	9993
#3	468	#3	9993	#3	9981
#0	350	#0	2839	#0	9908

7. Conclusions and Future Work

With more and more wireless micro-system are deployed in the Internet of Things, the cross technology interference problem become a hot topic. This paper focuses on the interference avoidance of ZigBee from WiFi networks and experimentally examines the spatio-temporal variation feature of WiFi interference which motivates us to use multichannel mechanism in ZigBee networks. We also analyzes the limitations of the existing interference assessment model based on SINR and propose an efficient interference detection approach which jointly considering the intensity and density to overcome the inherent limitations of the existing models.

We further design the MuZi protocol that augments multi-channel mechanism for ZigBee networks based on the assessing method. Different from the existing work, MuZi considers the locality of interference in time and space. Through experiments, we show that our proposed interference detection method is able to effectively distinguish between interferences at different severity levels. 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.

We have exploited the continuous frequency allocation for efficient spectrum utilization [Li et al. 2013], which combines location and frequency into one space and thus transforms the problem into a spatial tessellation problem. In the future, we will integrate this work with MuZi to further improve the efficiency of ZigBee networks.

Acknowledgments

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