Experimental Evaluation of Interference Mitigation on The 2.4 GHz ISM band Using Channel Hopping

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***Abstract*—Both research and practice have revealed that sensor devices running the 802.15.4 on their MAC layer may be competing for wireless communication on the 2.4 GHz ISM band with Wi-Fi, Bluetooth and other proprietary devices. Building upon a SunSPOT development platform, we evaluate the impact of channel hopping on interference mitigation in the 2.4 GHz ISM band and propose a channel hopping model that may be used to mitigate interference under different indoor WSN deployment scenarios. The results obtained by using a wireless sensor network where the sensor nodes are placed at different distances from an interference source and using different power levels agree with previous experimental works on interference in the 2.4GHz band and reveal that (1) channel hopping can improve the performance of WSNs when deployed in Wi-Fi collocating environments and (2) among the different parameters, the received signal strength indication (RSSI) is the most relevant for WSN performance evaluation in collocating Wi-Fi environments.**

I. Introduction

Both research and practice have revealed that sensor devices using the 802.15.4 standard [1]on their MAC layer may be competing for wireless communication in the 2.4 GHz ISM band with Wi-FI [2] and Bluetooth [3] devices. Furthermore various proprietary devices communicating using the same protocol standard are

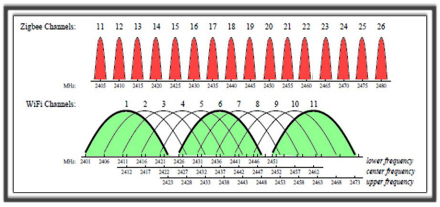

Fig. 1. *802.14.4 & 802.11 collocation*

emerging from niche applications into commodity products that add to this competition by sharing the same free ISM frequency band. As revealed by Figure 1, the interference between wireless sensor networks using the family of 802.15.4 protocols and Wi-FI networks using the family of 802.11.g protocols is a result of the frequency allocation by the IEEE standardization body leading to channel overlapping between 11 of the channels allocated to the 802.11 Wi-FI protocol and the 16 channels assigned to the 802.15.4 protocol in the 2.4 GHz ISM band. It can be seen from this figure that the frequency range of each IEEE 802.11 channel overlaps with the frequency ranges of four different IEEE 802.15.4 channels: e.g IEEE 802.11 channel 6 uses a frequency range which includes the frequency ranges for IEEE 802.15.4 channel 16 through channel 19. In a collocating environment, this might lead to radio interference caused by the 802.11 on the IEEE 802.15.4 channel 16 through channel 19 since (when deployed in the same environment), 802.11 devices operating at transmission power of order of magnitude 26 dBm can spatially affect the operation of 802.15.4 devices which operate at lower transmit power of 0 dBm. The frequency allocation map depicted by Figure 1 reveals that the 802.15.4 channels 25 and 26 use a frequency range outside of the frequency range for 802.11 channels to make provision for coexistence in a collocated environment. However, though being protected from WI-FI interference, these two channels may be subject to other sources of interference in the 2.4GHz band, especially in large-scale 802.15.4 systems. In such an occurrence, more channels need to be used to allow interference mitigation through frequency sharing.

The interference mitigation research has been investigated mainly through two types of studies: (1) empirical data studies which use experimental evaluation to obtain measured data based on a more practical testbed experimentation approach and (2) analytical studies which encompass modeling and simulation of elemental parts of the PHY and MAC behaviour. The work presented in [5] and later extended in [6] presents an experimental evaluation of the co-existence performance of IEEE 802.15.4 using a worst case scenario running the IEEE802.11b system with the highest possible utilization rate for a prolonged time, a scenario reported to have limited real world relevance. [4] covers co-existence with IEEE 802.11b/g by having the measurements made for different offsets between the central frequencies of the IEEE 802.15.4 and IEEE 802.11b/g channels. The paper shows that (1) there should be at least 7MHz offset between the operational frequencies for a satisfactory performance of the IEEE 802.15.4 and (2) using small packets of 20 bytes exhibits significantly better co-channel rejection than using the maximum packet size of 127 bytes. Using an IEEE 802.11g interferer with a data throughput of 9.8 Mbps in an office environment, the work in [7] show that for ZigBee nodes placed between 3 m and 6 m either side of the WLAN transmitter, the throughput is decreased by between 10% and 22%. The works presented in [10]- [12]

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are analytical studies. Using simulation based on the OPNET network simulator, and assuming that both the WLAN and LR-WPAN are transmitting blind, (without consideration for the channel state by using for example the carrier sense CCA mode (CCA-CS)), the work carried out in [10] reveals that (1) for a distance between the IEEE 802.15.4 and IEEE 802.11b longer than 8 m, the interference of the IEEE 802.11b does not affect the performance of the IEEE802.15.4 and (2) If the frequency offset is larger than 7 MHz, the interference effect of the IEEE 802.11b is negligible to the performance of the IEEE 802.15.4. The work presented in [10] is expanded further in [11] to consider the performance of an IEEE 802.15.4 link under the interference of a saturated IEEE 802.11b network. The work reveals (1) a significant increase in PER with the increase in transmitting WLAN nodes and (2) an IEEE 802.15.4 PER below 10% for separations of 8m and above (co-channel) when considering 20 WLAN nodes. Focussing on the PER analysis under the influence of WLAN and/or Bluetooth, the work presented in [12] shows that the Bluetooth interferer has much less of an effect on the IEEE 802.15.4 PER than WLAN.

The focus of this paper lies on experimental evaluation of interference mitigation in collocating WSN/Wi-Fi settings. Building upon a SunSPOT [13] experimental setting, the main contribution of this paper is to evaluate the performance of channel hopping at improving the performance of sensing activities in environments where wireless sensor network (using 802.15.4) devices, are competing for frequency, in the ISM band with collocated Wi-FI devices in different network settings, and using different power levels. The experimental evaluation is built around the following key features:

- *SunSPOT evaluation.* Interference mitigation in indoor settings is a key feature upon which the field readiness of a WSN platform depends. We propose in this paper an experimental evaluation of the SunSPOT platform for indoor interference mitigation.
- *Robustness of the evaluation.* Many performance metrics have been proposed in the standard SunSPOT toolkit offering for link quality measurement. Building upon an indoor setting, we evaluate the relevance of using each of these parameters under different network settings and power levels.
- *Channel hopping implementation.* Channel hopping has been investigated in many works as a potential solution for interference mitigation and implemented in wireless products as a solution for power saving and throughput maximization. Building upon these examples, we implemented a Java version of channel hopping on SunSPOT platforms and used it to evaluate its potential in collocated WSN/Wi-FI settings.

The remainder of this paper is as follows.In section II we present the interference mitigation model. Section III presents our performance evaluation while our conclusions are presented in section IV.

II. The Interference Mitigation Model

Building upon interference mitigation methods, we propose a cognitive frequency management model that autonomously coordinates the usage of spectrum on SunSPOT devices by (1) identifying the channel usage through energy scanning (2) classifying these channels into crowded and unused channels and (3) making decisions to hop from the crowded to the least used channels.

On the SunSPOT platform, the base station has two differing modes of operation [14] namely, the dedicated mode and the shared mode. In the dedicated mode, the base station and the host runs with the same Java VM (Virtual machine), this in turn also means that they share the same address for communications. Thus, in this mode, only a single host application can be managed at a time i.e. the base station is dedicated to a single host application. In the shared mode, two Java VMs are launched on the host computer. One manages the base station, while the other manages the host application. Hence, in this mode the host application and the base station have their own separate addresses. The advantage of this shared mode is that it allows the base station to communicate simultaneously with multiple applications running on the host, it also allows the applications to communicate with each other. The disadvantage of the shared mode is that it does not allow runtime manipulation of the base station's (and remote sensor node's) radio channel, PAN (Personal Area Network) identifier, and output power. This restriction makes it difficult to, automatically, scan through the frequency channels available to SunSPOT nodes. Thus in order for us to manipulate these parameters programmatically, we had to manually set the base station to dedicated mode (using the SunSPOT Manager program) as the SunSPOT is set to run in shared mode by default. Using the dedicated mode we developed a channel hopping algorithm which scans the available channels from the least interfering to the most interfering. While occupying these channels we would take temperature measurements along with measurements of differing performance parameters.

III. Experimental evaluation

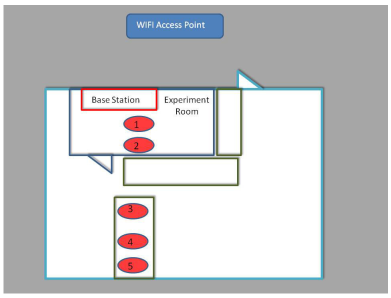


Fig. 2. *Experimental Setting*

Hopping the WSN frequency band between different Channels, and using different distances between a remote spot and the base station, at different times of the day, we conducted several experiments to evaluate the impact of different performance parameters on interference. These include

- RSSI Received signal strength indicator. This is a measure of the signal strength when receiving a packet. This is measurement is based on the reading of the remote spot. This ranges from +60 (strong) to -60 (weak)
- LQI Link Quality Indicator. This is a characterization of the quality of a received packet. Ranges from 0(bad) to 255(good).
- CORR Correlation value, This measures the average correlation value of the first 4 bytes of the packet header. It ranges from 110 (good) to 50 (poor).

A. Location of the experimental Testbed

Using a network located in the reception range of a competing Wi-Fi network used to provide wireless access to the department of computer science of the university of Cape Town, we conducted different experiments in the indoor environment depicted by Figure 2 where (1) the access point playing the role of interference source is located behind the WSN base station and (2) the receiving nodes are located in front of the base station in the opposite direction of the source of interference. All our measurements were taken using a SunSPOT network implementing a Java virtual machine above the 802.15.4 MAC layer. Using a single hop between the base station and the receiving remote node, we sent 20 packets (within each frequency band scanned) to the remote node. Each packet requested the receiving node to take the temperature reading at its location. The receiving node would then respond to each received packet with a reply packet which consisted of the temperature reading. Piggy backed on these packets would be performance related data that were described earlier. The readings were taken at differing power levels and at different distances (from the interfering source and the base station) for each channel scanned. These procedures were used in combination with off-the-shelf spectrum scanning software (collected from open source repositories) and our Java based channel hopping algorithm. From the results obtained, we classified the experiments into three groups according to the performance patterns obtained. These include (1) the experiments conducted at 50cm and 150cm with similar performance pattern (2) those conducted close to the interference source at 250cm and 485cm with a different pattern and (3) the experiments conducted at 750cm and 1000cm from the base station with their own performance pattern. For space limitation, only a subset of results from each group of experiments have been reported.

B. Experiment 1: Spot at 150cm from Base Station (Figure 3)

RSSI. *At -3dbm*: The RSSI readings continuously improve as it moves from channel 26 channel 11. We expected the readings to degrade when moving from ch26-ch11, as the Wifi interference source that we are monitoring has a central frequency that operates close to (IEEE 802.15.4) channel 12. This reveals that channel hopping does not necessarily mitigate interference when the sensor node is close to the interference source. The readings range from -8 to -20 decibels; an indication that the signal quality tends towards a poor level (the lowest RSSI value is -60). For the other two power levels (-*15dbm and -22dbm*) the pattern is similar to that shown in the -3dbm readings, except that the signal quality has degraded comparatively. This is most likely due to the reduction in the operating power level.

CORR. *At -3dbm and -15dbm*: Overall the CORR values seem to be constant throughout all the channels, but at -15dbm the signal quality is slightly lower. *At -22dbm*: the signal quality is very good with exception of a slight dip at ch13 and ch12 which is close to the center frequency of the Wi-Fi source. *Overall*: The CORR value (based on this graph) does not seem to give much indication of interference in the region. A possible reason for the positive readings maybe due to the short distance between the spot and the base station which can minimize the effect of interference.

LQI. The readings are similar through all the channels and all power levels.

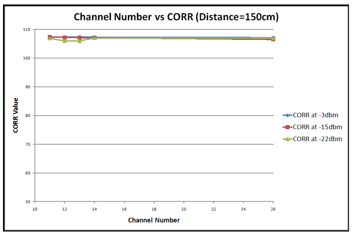
Overall. Out of the 3 Performance parameters, RSSI seemed to be the most sensitive to the interference source, giving readings which ranged from average to poor. Both LQI and CORR showed values which indicated that the signal quality is good.

C. Experiment2: Spot at 485cm from Base Station (Figure 4)

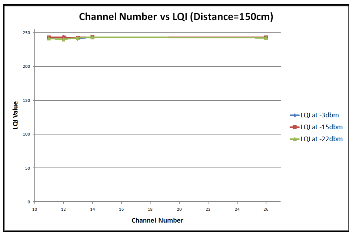
RSSI. On all power levels there is a dip in signal quality at ch13. This is close to the center frequency of the Wifi source, and thus may signify that the RSSI technique has picked up the presence of another wireless source which operates at an energy level which affects the RSSI readings. The readings then improve on ch12 and ch11 (the readings are even better than at ch26). The reason for the improvement maybe due to channel sharing techniques such as DSSS (Direct Sequence spread spectrum) which help the spot to communicate on channels where there may be wireless sources. Overall the signal quality as indicated by RSSI is poor. The chart also indicates that spots working at a lower power level is more susceptible to interference.

CORR. Overall the signal quality is good as indicated by CORR for all three power levels. It must be noted that while the readings here indicate a good quality signal, the number of packets being received by the base station (at power levels -15dbm and -22dbm) is fairly less than the number of packets sent (which is 20 packets) i.e. a good number of packets were getting dropped.

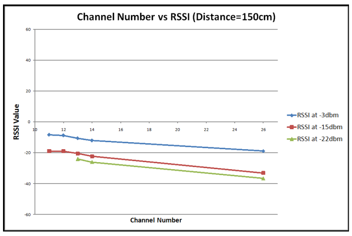
LQI. At power level -22dbm the drop in quality was quite significant. This is the first instance where the quality has dropped at ch14, thus this maybe due to some unknown interference source that was operating in that channel. Overall the signal quality has been indicated as good for all three power levels. In figure 4d it is indicated that when the LQI indicator was being used, the base station received 140% of the packets sent. This anomaly is difficult to explain, but is most probably due to the fact that we have utilized the UDP (User Datagram Protocol) protocol for communications. Duplication



(a) CORR at 150cm



(b) LQI at 150cm

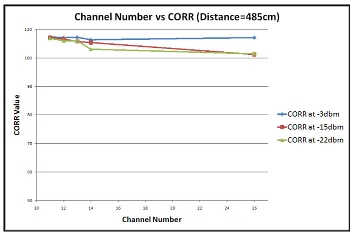


(c) RSSI at 150cm

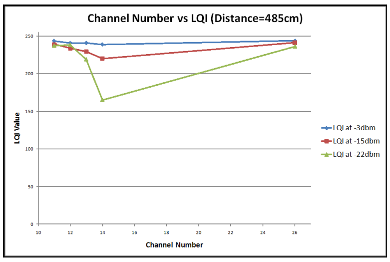
Fig. 3. *performance at 150cm*

of packets is one of its negative properties. What is more interesting is that this effect takes place at ch13, and thus the behavior can be attributed to the interference experienced in that channel.

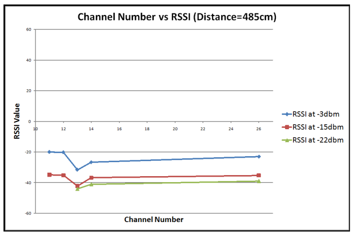
Overall. Out of the 3 Performance parameters, RSSI seemed most sensitive to the interference source, giving readings which ranged from average to poor. Both LQI and CORR showed values which indicated that the signal quality is good. This was not necessarily in agreement with the number of received packets (at the base station) which was less than what was sent. For all three indicators an increase in distance has led to a drop in the signal quality reading. It must be noted that as the power level is reduced it is expected that the number of packets received by the base station would reduce. So at this stage we can see that the combination of a lower operating power, greater distance, and the presence of interference is negatively affecting the performance of the WSN system.



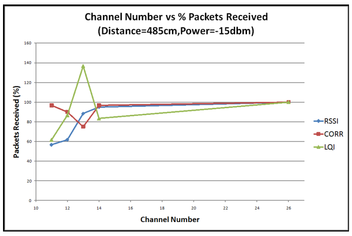
(a) CORR at 485cm



(b) LQI at 485cm



(c) RSSI at 485cm



(d) RCV at 485cm and -15dbm

Fig. 4. *performance at 485cm*

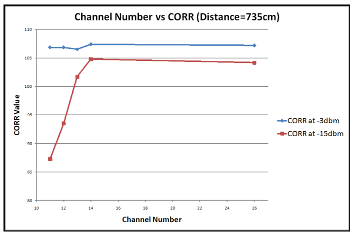
D. *Experiment3: Spot at 735cm from Base Station (Figure 5)*

RSSI.Only readings taken at the -3dbm power level were able to get recorded. At the other power levels packets did not get received by the base station, this maybe due to the increase in distance. at -3dbm power level there is a sharp increase at channel 12 which is difficult to explain since the behavior is not as expected.

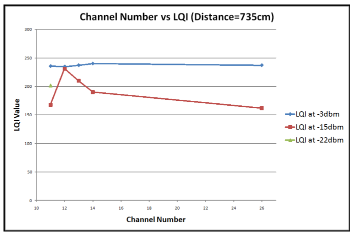
CORR. For power level -15dbm the signal quality steadily reduced from ch13-ch11. This is most probably due to the wifi interference source. No readings were possible at the -22dbm power level.

LQI. On power level -15dbm The signal quality seems to steadily improve from ch26 to ch12. With ch12 having a significant increase in signal quality. This is not expected, as we expect the signal quality to reduce when coming closer to ch12 (the operating channel of the Wifi source). But at ch11 the signal quality does drop significantly. No reading could be taken at the -22dbm power level.

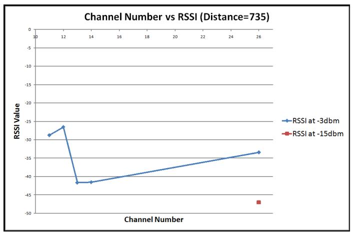
Overall. Out of the 3 Performance parameters, RSSI seemed most sensitive to the interference source, giving readings which ranged from average to poor. Both LQI and CORR showed values indicating that the signal quality is good. The reason for the discrepancy between the results provided by the different performance parameters is most likely due to the fact that RSSI checks the strength of the signal received at the base station whereas the other two techniques checks the quality of the packet received and based on this infers what the signal quality is. So, while the RSSI has indicated that there is interference in the area, the LQI and the CORR indicate that the interference is not significant enough to damage the packets that were received. Thus the RSSI parameter, based on these results, is better at detecting an interfering source within a region.



(a) CORR at 735cm



(b) LQI at 735cm



(c) RSSI at 735cm

Fig. 5. *performance at 735cm*

IV. Conclusion

Building upon the SunSPOT platform, this paper investigates the use of channel hopping to mitigate the interference between 802.11 and 802.15.4 protocols in indoor WSN deployment settings. The experimental results used to validate our model reveal that while the received signal strength indication (RSSI) seems to be the most appropriate parameter to be used for robust evaluation of wireless sensor networks in collocating WSN/Wi-FI environments, the Link Quality Indication (LQI) and CORR may lead to false efficiency indication. The results also reveal that channel hopping might not be useful when the sensor node is very close to the interference source. While our work is based on a proactive technique where the WSN nodes hop into a lightly populated frequency band upon detecting interference in a highly populated frequency band, it can be used in conjunction with a preemptive technique in a hybrid setting where the current and past states of the network are used in a cognition process to learn what is happening daily in the WSN environment, and based on this decide on the actions to take. This can be useful, for example, in campus network settings where specified frequency bands are most used during certain times of the day while others are unused. The study of this model has been reserved for future research work.

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