Can Frequency Diversity Provide Performance Gains for WSNs at 2.4GHz for the Fire Hydrant to Above Ground Channel

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***Abstract*— Wireless Sensor Networks (WSNs) which utilise IEEE 802.15.4 technology offer the potential for low cost deployment and maintenance compared with conventional wired sensor networks, enabling effective and efficient condition monitoring of aged civil engineering infrastructure. We will address wireless propagation for a below to above ground scenario where one of the wireless nodes is located in a below ground fire hydrant chamber to permit monitoring of the local water distribution network. Frequency Diversity (FD) is one method that can be used to combat the damaging effects of multipath fading and so improve the reliability of radio links. However, no quantitative investigation concerning the potential performance gains from the use of FD at 2.4GHz is available for the outlined scenario. In this paper, we try to answer this question by performing accurate propagation measurements using modified and calibrated off-the-shelf 802.15.4 based sensor nodes. These measurement results are also compared with those obtained from simulations that employ our Modified 2D Finite-Difference Time-Domain (FDTD) approach.**

I. Introduction

In recent years, Wireless Sensor Network (WSN) research has undergone a quiet revolution, providing a new paradigm for sensing and disseminating information from various environments using wireless technology. In practice, the successful and effective deployment of WSNs to monitor infrastructure, e.g., the local water distribution network, is challenging owing to the harsh radio propagation environment that disrupts the radio communication links between wireless nodes. For example, multipath induced channel fading and RF interference give rise to dramatic changes in the received signal strength and the consequent variability of the bit error rate (BER) of the communication links. Therefore in a static environment, if nodes happen to be located in areas experiencing deep signal fading, they will potentially suffer from long term poor link performance. The question has been raised as to whether we can apply Frequency Diversity (FD) techniques to WSNs in order to combat signal fading and so improve the coverage and robustness of WSNs.

FD has been studied in detail and implemented widely in cellular networks [1] in order to improve system BER performance and coverage. Due to the change in the wavelength of the transmitted signal with different operating frequencies, it is possible that the received signal power on different frequency channels can be quite different, i.e., by changing channels a node can effectively move itself out of a fade without need to be physically moved. Lemieux in [2] and Todd in [3] observed the improved performance due to frequency diversity (FD) in the indoor radio channels at 900MHz and 1.75GHz respectively for wireless personal communication. Generally speaking, FD has two main forms: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping. The IEEE 802.15.4/ZigBee compliant RF transceiver [4] used in the Crossbow Technology Inc. MicaZ radio node employed in our experiments utilises DSSS. Furthermore, Dust Networks Inc. has incorporated Frequency Hopping in their proprietary Time Synchronised Mesh Protocol (TSMP) [5], but quantitative results concerning the performance benefits have not been presented.

Consequently the potential benefits of applying FD needs to be quantified and characterised by performing accurate propagation channel measurements in the fire hydrant (FH) to above ground channel of interest. To do this in a realistic and inexpensive way we designed and built portable channel measurement equipment based on MicaZ motes from Crossbow Technology Inc. In this paper, we present an analysis of the RF performance of the equipment in order to establish its suitability for this task. The use of standard motes will also permit us to take channel measurements in situations that closely replicate actual WSN deployments. The Cross Correlation Coefficients (CCCs) of the fading data at various frequency channel spacings have been calculated using received signal power data gathered by scanning a number of channels in the unlicensed 2.4GHz band. In addition, these results have been compared with those obtained from a simulation that uses the modified 2D FDTD method [6].

The paper is organised as follows. Section II introduces the design of the portable equipment for RF channel measurements, calibration of the equipment, measurement procedures and the communication scenario for the FH to above ground link. This is followed in section III by the measurement results and comparisons with the simulation results yielded by the 2D FDTD method. Finally, Section IV draws our conclusions and also proposes future work.

II. Experimental Methodology

A. *Design of the Portable Equipment for RF Channel Measurements*

The RF channel measurement equipment design is based around standard off-the-shelf Crossbow MicaZ motes [7]. The equipment consists of two subsystems, one acting as the Transmitter Unit (TxU) and the other one acting as the Receiver Unit (RxU). Fig. 1 shows views of the TxU and the RxU.

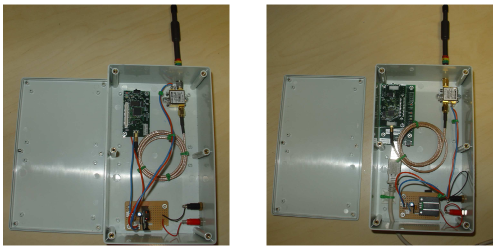

Fig. 1 Top views of the TxU on the left and the RxU on the right

1) The Transmitter Unit: The TxU shown on the left in Fig. 1 has three main components: one Processor and Radio MPR2400CA board (top left), one power amplifier ZX60-2522M+ with a gain of 19.5dB [8] (top right) and one Step-Down Integrated Switching Regulator (ISR) PT79ST133 [9] (bottom left). They are all housed in a plastic enclosure of dimensions 19.3cm by 11.3cm by 5.8cm. The CC2420 RF transceiver is mounted on the MPR2400CA board for the purpose of wireless communication. It is a single-chip 2.4GHz IEEE 802.15.4 compliant RF transceiver designed for low power and low voltage wireless application. The MicaZ's CC2420 radio can be tuned from 2.048 to 3.072GHz which includes the global ISM band at 2.4GHz. IEEE 802.15.4 channels are numbered from 11 (2.405GHz) to 26 (2.480GHz) each separated by 5MHz. The use of the transmitter power amplifier permits us to conduct extended range channel measurement campaigns in RF-hostile environments, such as the FH to above ground channel.

2) The Receiver Unit: The CC2420 radio chip used in the Crossbow mote provides a very important piece of metadata about received packets, specifically the Receive Signal Strength Indication (RSSI), which is a measurement of the received signal power in dBm. It is calculated over the first eight symbols after the start of a received packet. RSSI can also be measured at other times, for example to detect the ambient RF energy [10]. We use this feature to calibrate the receiver as will be described in Section II-B. The design of the RxU shown on the right in Fig. 1 is very similar to that of the TxU except it also has a mote interface board (MIB520) enabling RSSI data to be downloaded to a laptop PC. The four key components are: one Processor and Radio MPR2400CA board (top left), one MIB520 interface board on top of which the MPR2400CA board is attached, one low noise amplifier (LNA) ZX60-33LN+ [11] (top right) and one ISR 78SR105HC [12] (bottom). The LNA (ZX60-33LN+) has a gain of 13.5dB and improves the sensitivity of the receiver system by about 12dB over that of the standard mote. The plastic enclosure for RxU has the same dimensions as that for TxU. The incorporation of the amplifier into the RxU further increases the channel measurement range and gives us greater freedom in the choice of measurement points.

B. *Calibration of the TxU and the RxU*

As has been identified in [13], in general, the off-the-shelf MicaZ motes that we have tested have a RF performance below the manufacturers' quoted specifications, and in addition, their characteristics vary from one to another. This is generally accepted owing to their relatively low cost and low power consumption. However, conducting measurements using uncalibrated motes is not to be recommended [14], [15]. Specifically, it is necessary to calibrate the TxU and the RxU before attempting the propagation measurements needed to quantify the availability of FD.

The mote variability can be overcome using the method proposed in [13] for calibrating pairs of motes using a networked computer driven instrument system. The method uses a MATLAB based computational environment running on a host PC to control a RF signal generator (SG), or a spectrum analyser (SA) depending whether the RxU or the TxU is being calibrated respectively in an unattended manner. These measures enable accurate estimation of channel path loss over the frequency band of interest to be performed.

1) The RxU Calibration: The calibration subsystem for the RxU is designed to eliminate the hardware dependency by creating an accurate mapping between the RSSI values and the actual received power at the RxU antenna connector for all channels on which measurements are going to be performed. Fig. 2 shows the channel 11 lookup table after the calibration process and processing.

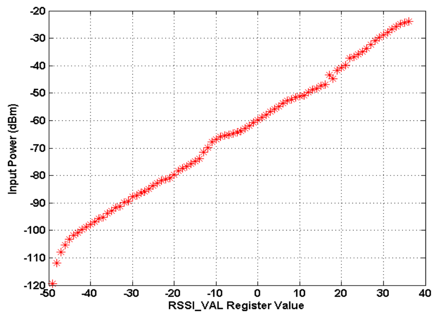

Fig. 2 Lookup table for the RxU under test after the processing for channel 11

2) The TxU Calibration: The calibration subsystem for the TxU is used to establish a lookup table for the transmit power from the TxU's RF connector as a function of frequency channel as shown in Fig. 3. The calibration process will considerably reduce errors owing to the variation in transmit power on different frequency channels, which is mainly contributed by the hardware characteristics of the CC2420 transceiver itself.

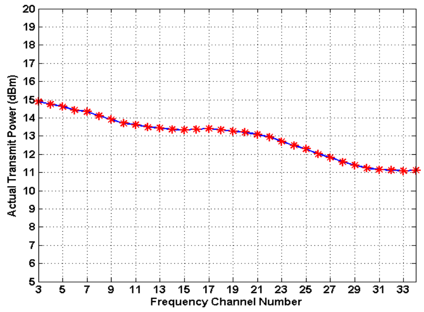

Fig. 3 Lookup table of the TxU under test across 32 frequency channels from 2.365GHz (channel 3) to 2.520GHz (channel 34) each separated by 5MHz

C. Experimental Set-up

In our FD channel measurements, the TxU was positioned in a below ground FH chamber located outside the Computer Laboratory building in Cambridge. The RxU was set at a height of 6.25m above ground level, representative of the height of a WSN node sited on a street lamp pole. Fig. 4 shows the FH chamber (with the iron lid removed) containing a standard Series 29-299 (119) PN Underground FH. The TxU antenna was located at the same height as the stem cap and 10cm away from it in the South direction along the central axis. Note the iron lid is in place during the measurements.

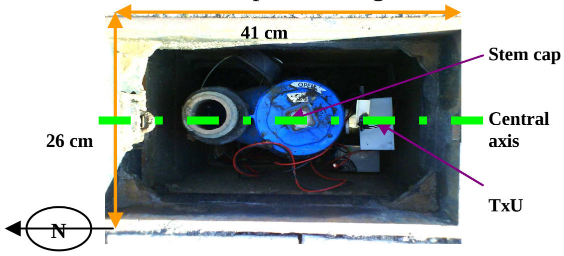

Fig. 4 Overview of the FH chamber (lid-off)

To assess the availability of FD the TxU and the RxU were programmed to hop through 32 frequency channels from 2.365GHz (channel 3) to 2.520GHz (channel 34), with a channel spacing of 5MHz. The TxU/RxU was programmed to transmit/receive a packet every 0.25s and to remain on each of the 32 radio channels for 1s. The above ground RxU records the received packets and their received signal power at varying distances from the TxU. The RxU position varied between 10m and 100m in steps of 10m in both the North and South directions from FH chamber. The RxU was stationary for 9 minutes while the data was gathered. The scanning of 32 frequency channels enables us to achieve a statistically significant understanding of the FD performance as a function of the channel spacing for spacings of up to 17 channels in the 2.4GHz band.

III. Field Measurements Results and Analysis

FD is a technique to combat the fading phenomenon by transmitting information on more than one carrier frequency. By doing this, the hope is to find independent signal paths for communication so that if one radio channel undergoes a deep fade, i.e., high attenuation, another independent channel may have a strong signal, i.e., low attenuation [16]. We choose to define propagation Path Loss (PL) as a positive value representing the signal attenuation measured in dB. To avoid confusion, here we define the PL in dB as:

$$PL = P_{Tx} + G_{Tx} + G_{Rx} - P_{Rx}, \qquad (1)$$

where P_{Tx} is the transmit power at the TxU RF connector, P_{Rx} is the receive power at the RxU RF connector, G_{Tx} and G_{Rx} are the transmit and receive antenna gain respectively. P_{Tx} and P_{Rx} are obtained from the calibration tables established in Section II-B according to the operating frequency on which the data packets are transmitted.

The success of the FD technique depends on the degree to which the PL performances on the different diversity branches are uncorrelated. We define the channel Cross Correlation Coefficient (CCC) ρ between the two diversity channels as shown in 2. It is calculated by normalising the cross correlation of the signals in the pairs of channels having the desired channel spacing,

$$\rho = \frac{1/N \sum_{n=1}^{N} x[n]y[n]}{\sqrt{(1/N \sum_{n=1}^{N} x[n]x[n])(1/N \sum_{n=1}^{N} y[n]y[n])}}, \qquad (2)$$

where x and y are the power gain sequences, and N is the number of samples used in each sequence. The elements of each sequence are negated PL values in dB converted to a linear ratio. Note the power gain (which is < 1) is used since it is directly proportional to the received power.

As a result, we adopt the method in [17] to present ρ in a matrix format shown in Fig. 5, where $\rho_{i,j}$ is the CCC value at the antenna separation represented by distance index i for a particular channel spacing represented by index j. The maximum value of i is set to 10, where the actual distance is equal to ($i\times10$)m, and that of j is set to 17 which ensures that a minimum of 15 pairs of channels to create the x and y sequences.

$$\text{Distance (10-100m)} \left\{ \underbrace{\begin{matrix} \rho_{1,1} & \rho_{1,2} & \rho_{1,3} & \cdots & \rho_{1,j} \\ \rho_{2,1} & \rho_{2,2} & \rho_{2,3} & \cdots & \rho_{2,j} \\ \rho_{3,1} & \rho_{3,2} & \rho_{3,3} & \cdots & \rho_{3,j} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \rho_{i,1} & \rho_{i,2} & \rho_{i,3} & \cdots & \rho_{i,j} \end{matrix}}_{\text{Channel Spacing (1-17)}} \right.$$

Fig. 5 Matrix representation of ρ

So for example, the value of $\rho_{1,10}$ at an antenna separation of 10m and with a channel spacing of 10 is calculated by arranging x as the combination of all samples recorded at 10m from channel 3 (the lowest frequency channel we scan) to channel 17 and y as the combination of all samples recorded from channel 13 to channel to channel 27 at the same distance.

Theoretically, frequencies separated by more than the coherence bandwidth of the channel will be uncorrelated and will thus not experience similar fading [2]. Note our normalised CCC values lie between 0 and 1. Calculations presented in [18] show that correlation coefficients as high as 0.7 are commonly used to define the coherence bandwidth. Note that greater gains are available from FD for smaller correlation coefficients. The CCC results are presented in two averaged forms, specifically as a function of channel spacing and also as a function of distance. Fig. 6 shows the plot of average CCC as a function of channel spacing based on measurement results and those obtained from the FDTD simulations. The average CCC is calculated by averaging over all distances in both South and North directions. The plot reveals the minimum channel spacing required in order to achieve a reasonable FD gain. As can be seen from Fig. 6, the CCCs are generally well above the critical value of 0.7, and there is no evidence to suggest any benefit owing to FD for channel spacings of less than 17. However, there is a decreasing trend as the channel spacing increases, implying that FD may give some improvements for greater channel spacings. The FDTD simulation results are reasonably similar to the measurement results.

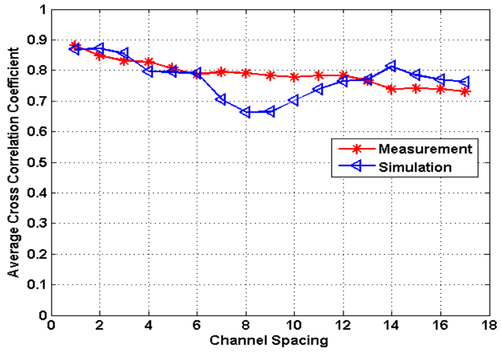

Fig. 6 Frequency diversity performance w.r.t channel spacing

Fig. 7 shows the average CCC as a function of distance, which is calculated by averaging over all frequencies at each distance. We observe a decreasing trend of average CCC as the distance increases in both north and south directions. Both measurement and simulation results suggest some benefits may result from applying FD at longer distances. Some deviation is apparent between the measurement and the simulation results. However, we believe that the difference is because the high resolution simulation results show details of the average CCC that are not revealed by the much lower resolution (i.e., 10m compared with 0.01m) of the measurement results.

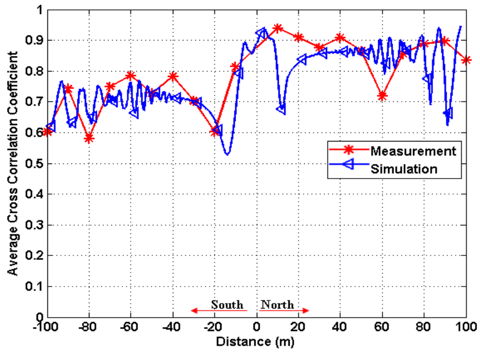

Fig. 7 Frequency diversity performance w.r.t distance

IV. CONCLUSIONS

Measurements have been conducted at 32 frequency channels in the 2.4GHz band in order to investigate and quantify the potential benefits of FD for WSNs deployed in the FH to above ground scenario.

The results suggest applying FD has little benefit for this channel, particularly at short communication range. However, some benefits appear to be available at longer range. This will be investigated in our future work. Field measurements with higher spatial resolution will also be conducted in order to reveal more information concerning the average CCC of this channel.

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REFERENCES

[1] J. D. Gibson, *The mobile communications handbook*. IEEE press, 2000.
[2] J. Lemieux, M. El-Tanany, and H. Hafez, "Experimental evaluation of space/frequency/polarization diversity in the indoor wireless channel," *IEEE Transactions on Vehicular Technology*, vol. 40, no. 3, pp. 569-574, 1991.
[3] S. Todd, M. El-Tanany, and S. Mahmoud, "Space and frequency diversity measurements of the 1.7 GHz indoor radio channel using a four-branch receiver," *IEEE Transactions on Vehicular Technology*, vol. 40, no. 3, pp. 312-320, 1992.
[4] A. Chipcon, "CC2420 2.4 GHz IEEE 802.15.4/ZigBee-ready RF Transceiver," *Chipcon AS, Oslo, Norway*, vol. 4, 2004.
[5] *Technical overview of time synchronized mesh protocol (TSMP)*, Dust Networks, Nov. 2008. [Online]. Available: http://www.dustnetworks.com/technology/
[6] Y. Wu, M. Lin, and I. Wassell, "Modified 2D Finite-Difference Time-Domain Based Tunnel Path Loss Prediction for Wireless Sensor Network Applications," *Journal of Communications*, vol. 4, no. 4, p. 215, 2009.
[7] "MICAz Datasheet," Crossbow Technology Inc., U.S.A.
[8] "ZX60-2522M+ Datasheet," Mini-Circuits, U.S.A.
[9] PT78ST100 series Datasheet," Texas Instruments Inc., U.S.A.
[10] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis, "Understanding the causes of packet delivery success and failure in dense wireless sensor networks," in *Proceedings of the 4th international conference on Embedded networked sensor systems*. ACM New York, NY, USA, 2006, pp. 419-420.
[11] "ZX60-33LN+ Datasheet," Mini-Circuits, U.S.A.
[12] "78SR105HC Datasheet," Texas Instruments Inc., U.S.A.
[13] R. Liu and I. J. Wassell, "A novel auto-calibration system for wireless sensor motes," University of Cambridge, Tech. Rep. UCAM-CL-TR-727, 2008.
[14] S. Saha and R. Bajcsy, "System design issues for applications using wireless sensor networks," Automated Learning Group, National Center for Supercomputing Application, Tech. Rep. alg03, 2003.
[15] Y. Yao and J. Gehrke, "The cougar approach to in-network query processing in sensor networks," *ACM Sigmod Record*, vol. 31, no. 3, pp. 9-18, 2002.
[16] T. Rappaport, *Wireless communications: Principles and Practice.* Prentice Hall PTR Upper Saddle River, NJ, 2002.
[17] Y. Wu, R. Liu, M. Lin, I. J. Wassell, "Frequency Diversity Evaluation using Modified 2D Finite-Difference Time-Domain Technique for Tunnel and Fire Hydrant Path Loss Models," *the 11th Biennial International Conference on Electromagnetics in Advanced Application*, Torino, Italy.
[18] W. Jakes, *Microwave mobile communications.* Wiley-IEEE Press, 1994.