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A STUDY ON PATH LOSS FOR INDOOR WIRELESS COMMUNICATION NETWORKS

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ABSTRACT

Design and deployment of a wireless communication networks require being able to model the path loss as realistic as possible. In this paper, several indoor empirical models to estimate path loss studies were studied and the standard deviations introduced by the models were compared, considering the complexity of indoor measurement environment in terms of the layout of the objects. The empirical model which assumes the path loss as the summation of free space loss and the individual losses introduced by each partition of any kind of material lying on the direct line between the transmitter and receiver, was critically decided to be the prominent model. Regarding it as the theoretical model to validate, experiments were conducted across several scenarios, by means of programming CC2420 motes and taking measurements via TinyOS. Some solutions were developed to overcome the inability of swept tuned spectrum analyser equipment to capture transient type signals transmitted from the motes. In addition to attempts to validate the theoretical model, TinyOS based experiments also consists of determination of practical input antenna gain of the CC2420 motes as well as measurements of observer effect, message issuing frequency effect, and path loss values of doors and walls and some other objects in the environment.

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ACRONYMS

cm	Centimeter
dB	Decibel
dBm	Decibel relative to one milliwatt
GHz	Gigahertz
KHz	Kilohertz
LED	Light emitting diode
LOS	Line of sight
m	Meter
MHz	Megahertz
ms	Milliseconds
RSSI	Received signal strength indicator
T-R	Transmitter-Receiver
VI	Virtual Instrument

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INTRODUCTION

Path loss is the attenuation of a signal radiated from a transmitter due to the distance travelled and characteristics of propagation channel.

Signal coverage and power constrain aspects are two main issues for engineers who wants to get involved in design and deployment of a wireless communication network. Both of them requires being able to model the path loss as realistic as possible.

This is an experimental study about path loss for indoor wireless sensor networks. The main goal is to validate some of the related literature and to contribution to it if possible.

The first chapter presents the related work. In the first section a brief theoretical background for path loss is provided. The second section introduces a literature review of various empirical models developed by researchers to estimate the path loss, especially with respect to indoor wireless environments.

In the second chapter, analytical and empirical indoor path loss models are critically analysed. The parameters and the related models are compared and the prominent model is further discussed in terms of future use. It is also regarded as the theoretical model to validate with the experiments.

The third chapter is about setting up the experimental phase of the project consisting of several stages. Learning how to programme CC2420 wireless sensor network motes with respect to being either in base station or transmitter mode, setting various output power levels, frequency channels and message issuing frequencies as well as taking RSSI measurements via TinyOS are the major components. The existing NI-PXI equipment was

studied in terms of setting it up as spectrum analyser and configuring for 2.4 GHz measurements. CC2420 wireless sensor network motes and NI-PXI equipment were provided by Department of Computer and Communication Engineering in Middlesex University.

The fourth chapter presents the implementation. It mainly consists of attempts to validate the partition dependent empirical model which were selected in the critical analysis section as the most successful one in terms of estimation. There are two sets of measurements with respect to measurement equipment, measurements with NI PXI equipment and measurements with TinyOS. The latter also includes measurements of observer effect, message issuing frequency effect, and path loss values of doors and walls and some other objects in the environment. Six different scenarios were implemented in Hendon Town Hall and Middlesex University Hatchcroft buildings. The results and findings as well as the analysis of them are presented.

Conclusion chapter is followed by appendices providing installation details of TinyOS, some photos from measurement environment and Hendon Town Hall Risk Assessment form submitted to the security administration in order to conduct the experiments in the building.

1. RELATED WORK

1.1. Theory

Path loss is defined as the attenuation of a signal radiated from a transmitter dependent on the distance travelled and various factors of the propagation channel. It is a well-known fact that the power of a signal decreases inversely proportional with the square of the distance from the transmitter. According to the Friis's Law [1], in free space, the ratio of received power (P_R) of a signal of wavelength λ at a distance d from the transmitter to the transmitted power (P_T) radiated from an ideal isotropic antenna is given as

$$\frac{P_R}{P_T} = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{1}$$

Taking the logarithm of both sides of (1) and multiplying by 10, we can express the path loss in decibels (L_P) as shown below

$$L_P = L_0 + 20\log(d)$$
 (2)

where L_0 is the path loss with respect to 1 meter transmitter –receiver (T-R) separation. Since the product of wavelength and frequency (f) of a signal is the well known constant of velocity of light (c) in free space, L_0 is a constant value for a specific frequency which is given by $L_0 = 20 \log(4\pi/(c/f))$, for e.g., it can be computed as approximately 40 dB for 2.4 GHz.

Furthermore, an excess path loss term (L_{PE}) can be defined as the difference of free space path loss from L_0 given as

$$L_{PE} = 20\log(d) \tag{3}$$

which will be regarded as simply path loss in the following literature review section.

1.2. Literature Review of Statistical Models

Several models have been developed by researchers to estimate path loss for indoor and outdoor wireless communications. Since, path-loss is a function of distance; researchers usually have focused on different distance dependent models.

Regarding outdoor environments, experimental studies such as [5] - [19] presented T-R separation distance dependent path loss models for various frequencies, terrain conditions and antenna positions in specific scenarios.

Indoor environments have also been interested in by various researchers. In [20] - [22], pure distance dependant models were introduced. Some researchers [23], [24] extended the model with the combination of distance and number of floors that the signal traversed. Similarly [4], [25] and [26] included a factor representing the number and type of walls between the source and signal. Some other studies [27], [28] conducted measurements to develop partition-dependent models.

Most important approaches to developing those empirical models are given in the rest of this section. Those indoor studies were conducted in the frequencies ranging from 900 MHz to 5.25 GHz.

In [23], [27] and [28], a single slope model was presented as a modification to (3) as

$$L_{PE} = 10n \log(d) + X_{\sigma} \tag{4}$$

where n is the path loss coefficient for the indoor environment in question, which is accepted as 2 for free-space. The X_{σ} term represents the standard deviation of a model caused by long-scale fading, which is well known to take a log-normal zero mean distribution. In other words, with the addition of that term, it can be concluded that, statistically 68% of the measurement results are confined in the neighbourhood of $\pm X_{\sigma}$ decibels of the computed value for an empirical model. Standard deviation of a model is a good measure of how accurately the model estimates the real values.

Equation (4) was transformed into a multi-slope model by [29] so that the equation was partitioned with respect to certain distance intervals, considering the breakpoints observed in the graph introduced by (4).

Some researches extended (4) by adding attenuation factors of floors, walls or soft partitions lying on the line from the transmitter to the receiver. In [22] – [24], the model was introduced as

$$L_{PE} = 10n \log(d) + FAF + X_{\sigma}$$
 (5)

where FAF represents either an average floor attenuation factor per floor times the number of total floors (ΣFAF_{avg}) or a single attenuation factor assigned for a specific number of floors in the environment (FAF_k).

Similarly, in [30], the FAF term in (5) took the form of wall attenuation factor (WAF) given as

$$L_{PE} = 10n \log(d) + WAF + X_{\sigma}$$
 (6)

In [23], (5) and (6) were modified further by taking n equal to 2 and considering the soft partition and concrete walls so that

$$L_{PE} = 20 \log(d) + p * sAF + q * cAF + X_{\sigma}$$
(7)

where sAF refers to the soft partition attenuation factor, p refers to the total number of soft partitions on the direct line between the transmitter and receiver, cAF stands for concrete wall attenuation factor and q stands for total number of concrete walls.

In [4], beginning with taking the path loss coefficient for free space, (4) was extended to consider the observed reduction of path loss per wall as the number of walls increase so that

$$L_{PE} = 20 \log(d) + L_{S} n_{S}^{(\frac{n_{S}+5}{n_{S}+3}-b)} + X_{\sigma}$$
 (8)

where L_S is meant to be the average path loss per wall, n_S is number of total walls that the signal traverses through and b is an empirical parameter to compensate for the aforementioned reduction.

The study in [30] has contributed to the literature by modifying (6) with the addition of a scalar parameter α that stands for the path loss in decibels per meter in addition to the free space path loss and path loss introduced by walls in terms of wall attenuation factor such as

$$L_{PE} = 20 \log(d) + \alpha d + WAF + X_{\sigma}$$
(9)

In [27] and [28], the empirical model was developed based on the intuitive assumption that total path loss can be thought as the summation of free space loss and the individual losses introduced by each partition of any kind of material lying on the direct line between the transmitter and receiver so that

$$L_{PE} = 20 \log(d) + \Sigma m_{type} w_{type} + X_{\sigma}$$
(10)

where, m_{type} stands for the number of objects of the same kind and w_{type} is the loss in decibels related to that specific object.

2. CRITICAL ANALYSIS

Modelling the path loss in an indoor wireless communication environment is essential for design and deployment of the network, regarding especially signal coverage and power constrain aspects [1], [2].

Due to the nature of most indoor environments, radio signals are subject to unpredictable cumulative effects of absorption, reflection, refraction, scattering and diffraction caused by objects such as walls, floors and other obstacles; so it is practically impossible to develop an accurate general analytical model for path loss [3]. Moreover, as shown in [4], it is quite difficult and tedious to accurately model a given specific environment due to the nonhomogenous structural characteristics of aforementioned obstacles. Instead, it is more convenient to develop statistical models based on empirical measurements

On the other hand, as discussed in [3], those models somewhat depend on the specific characteristics of the environments in which the measurements were conducted, thus leading to arguable validity of them to be generalized.

Researchers began with the suggestion of an intuitive empirical model, which is a mathematical expression of the path loss dependent on distance and some other empirical parameters. They conducted measurements and used the results to find the parameters of their models. Then, comparing the measured results and the results offered by their models, they presented how closely their model represents the real environment.

Equation (3) provides a linear relationship between path loss and T-R separation in logarithmic scale. However, when measured in a realistic environment, the received signal strength indicator (RSSI) exhibits some slow and fast fluctuations along the major decreasing trend of free space

loss. Slow fluctuations are mainly due to the shadowing effects of the objects on the line of sight (LOS) and sometimes called large-scale fading. Fast ones are observed with respect to distances in the order of the signal's wavelength and called small-scale or multi-path fading [3]. Since the multi-path components arrive in different phases, they have destructive and constructive effects on the strength of the received signal, thus leading fluctuations as the measurement point is moved in the order of wavelength distance.

It was shown that [23], along 20 λ tracks, the phases of arriving multi-path components of a signal exhibits uniform distribution, i.e., they are uncorrelated from each other. So, all of the researches who wanted to mitigate the effects of multi-path fading, used the technique of averaging the measurement results over distances of several wavelengths and they usually regarded that average value as a single measurement result of the local area defined by the track.

On the other hand, researchers introduced some additional terms to (3) in order to better estimate the large-scale fading. Afterwards they conducted their measurements and used the results to fit into their empirical models by using linear regression with minimum square error technique. That way they found the parameters in their models and finally compared the results produced by the models to the real measurement results to find the standard deviation of their models.

The standard deviations introduced by the models are important indicators of success of estimation. However, the complexity of indoor measurement environment in terms of the layout of the objects such as floors, walls and other materials is still a major factor so the deviation parameter cannot be sufficient to measure the success of estimation alone. Below is given a table providing the standard deviation values in decibels of the aforementioned

studies with respect to the models/equations they are based on as well as a basic classification of the layout.

Model (Equation)	Ref.	Measurements across	X _σ [dB]
	[28]	Single floor	5.8
	[27]	Multiple buildings overall	8
(4)		Multiple buildings overall	16.3
	[23]	Multiple buildings – same floor measurements overall	12.8
Multi-slope	[29]	Single floor	2.1
(5)	[22]-[24]	Single building multiple floors	4.8 – 7.2
(6)	[30]	Single floor	3.2
	[23]	Multiple buildings overall	5.8
(7)		Multiple buildings –same floor measurements overall	4.1
(8)	[4]	Single floor	4
(9)	[30]	Single floor	3.4
	[28]	Single floor	1.4 – 2.3 (various materials)
(10)	[27]	Multiple buildings overall	2.3 (plaster partitions)
	[21]		3.4 (plasterboard partitions)

Table 1: Standart deviations related to various models

Comparison of the standard deviations given in the table should be done under different layout types. According to the measurements that were conducted in a single floor, (10) seems to lead in terms of success of estimation. Multi-slope model also displays a similar performance but it is thought that selection of break-point distances can heavily affect the estimation. In more complex scenarios such as the multiple buildings with multiple floors, (10) also gives the minimum deviations for several kinds of partitions. Accordingly, it has been concluded that the empirical model which assumes the path loss as the summation of free space loss and the individual losses introduced by each partition of any kind of material lying on the direct line between the transmitter and receiver, is the preferable method to be used when modelling the path loss in an indoor wireless communication environment.

Indeed, the empirical model introduced by (10) has been adopted by several researchers. In [2], a simulation – based performance evaluation was presented to help optimization of wireless sensor network motes' transmitter power levels in order to minimize packet retransmissions and maximize the network life time. However, to be able to yield more accurate results, that kind of studies need partition dependent path loss values for a wide range of material types, provided for the frequency of concern and given in a per unit width basis. Some tables were provided for partition-dependent path loss for different materials, especially [31] presents the longest table in the literature, but those values are either for different frequencies, or do not provide the sufficient length or detail. It will be useful for the future studies to provide partition-dependent tables for a wide range of materials.

When dealing with measurement of path-loss values attributed to different kind of materials, the ideal technique will be the measurement of the difference of RSSI values with and without the material on the direct line between the transmitter and receiver as stated in [32]. The key point is the elimination of small-scale fading by averaging the measurement results on a track of several wavelengths, as has been done in previous researches. Also, multi-path component should not be dominating the received signal power. The received power of an indoor multi-path component is mainly dependent on the distance that the signal has travelled as well as the dissipated power on the reflected surface [33]. It was shown in [34] that in a typical indoor environment, the dissipated power on a wall is around 20 decibels. On the other hand, it was given in [31] that the transmission losses introduced by most of the materials are less than 10 decibels, which makes the aforementioned technique feasible. If the material of question is thought to have a higher transmission loss, the measurements can be conducted by placing the transmitter or receiver to a closed box of that material in order to eliminate the high power multi-path components at the measurement point.

The empirical model assuming the path loss as the summation of free space loss and the individual losses introduced by each partition of any kind of material lying on the direct line between the transmitter and receiver, is the most successful model in terms of estimation, which was validated to yield the least standard deviations in different kind of environments. However, designers/researchers who want to use that model, lack longer or more detailed tables of path loss values. A study involving measurements of those values will be a useful future work.

3. EXPERIMENTAL SETUP

3.1. Mote Programming

3.1.1. CC2420 motes introduction

Throughout the experiments, 5 pieces of CC2420 motes were used. CC2420 is an IEEE 802.15.4 compliant RF transceiver especially designed for wireless sensor network applications. It operates in the 2.4 GHz ISM band. Its built-in baseband modem provides digital direct sequence spread spectrum with 250 kbps data rate and 2 Mchip/s chip rate. Its output power and various parameters are programmable by the use of TinyOS. Readers are referred to the web site of vendor for more detailed technical specifications and data sheet. ¹

In a simple classical wireless sensor network topology, there are sensor motes collecting some kind of information and delivering it to a gateway mote. Similarly, during the experiments, one of the motes was configured as the gateway or base station in other words. All or some of the rest were configured as sensor motes i.e. transmitters.

3.1.2. TinyOS Introduction

TinyOS is an operating system as the name implies. It was specifically designed for programming low-power integrated platforms just as the motes used in wireless sensor networks. It is free and open source, written in nesC programming language, a variation of the C language optimized for the memory restricts of the motes.

¹ http://www.advanticsys.com/shop/asxm1000-p-24.html

The architecture of TinyOS simply makes use of a scheduler on top of an application layer followed by various libraries and finally a hardware abstraction layer providing the interface to physical components of the motes such as the clock, LEDs, etc.

Simply, the nesC compiler loads in some nesC components and compiles them into a C file, followed by a native C compiler producing the binary code required to be loaded onto motes.

Components are the basic units of the nesC code. They connect via interfaces which actually represent the wiring between components. There are two types of components: modules and configurations. Modules are the components including the variables and the executable code. Configurations are the ones which wire other components in between themselves, in other words they provide abstractions for modules.

Below are the simple built-in module and configuration components to power up a mote, respectively. The module uses the Boot and Leds interfaces to wire itself to the MainC and LedsC components via the pointers in the configuration component.

```
PowerupC {
    use interface Boot;
    use interface Leds;
}
implementation {
    event void Boot.booted();
        call Leds.led0On();
    }
}
PowerupAppC {}
implementation {
```

components MainC, LedsC, PowerupC; PowerupC.Boot->MainC.Boot; PowerupC.Leds->LedsC.Leds;

Interfaces are the collections of related functions and they represent the interactions between components. They are either in the form of commands or events. Events are called by the provider component and implemented by the user component, commands are vice versa. In the previous example, interface Boot let the components know when TinyOS boots.

TinyOS makes a hierarchical use of makefiles which allows the programmers to easily configure various parameters like the output power.

3.1.3. TinyOS installation

}

TinyOS were installed adopting the recommended method by CC2420 vendor.² The installation details are provided in Appendix A.

3.1.4. Making use of demoTinyOS applications

TinyOS provides sample applications such as Blink, RssiDemo, etc. As mentioned before TinyOS applications can be compiled with *make* command. Make system allows the users to easily add new platforms like telosb as well as different compilation options. Makefile definitions are located in the /support/make file under the related TinyOS installation folder. To compile any application, make command is executed in the specific application folder followed by the platform name. So that, navigating into the /opt/tinyos-XM1000/apps/tutorials/Blink folder and running the command

make telosb

² http://www.advanticsys.com/wiki/index.php?title=TinyOS_Installation_Guide

produces such an output:

compiling BlinkAppC to a telosb binary

```
ncc -o build/telosb/main.exe -Os -fnesc-separator=__ -Wall -Wshadow -Wnesc-all -
target=telosb -fnesc-cfile=build/telosb/app.c -board= -DDEFINED_TOS_AM_GROUP=0x22 -
DIDENT_APPNAME=\"BlinkAppC\" -DIDENT_USERNAME=\"root\" -
DIDENT_HOSTNAME=\"ubuntu\" -DIDENT_USERHASH=0xa3473ba6L -
DIDENT_TIMESTAMP=0x522de883L -DIDENT_UIDHASH=0x2556350bL BlinkAppC.nc -Im
compiled BlinkAppC to build/telosb/main.exe
2528 bytes in ROM
56 bytes in RAM
msp430-objcopy --output-target=ihex build/telosb/main.exe build/telosb/main.ihex
writing TOS image
```

The output tells us that the module named BlinkAppC in the Blink folder is compiled with the given parameters and a binary image is produced ready to be installed on a telosb mote.

The next step was installing that image onto a mote. CC2420 motes, which belong to telosb family, can be plugged on any USB port, as shown in the photo of the setup environment below.



Figure 1: WSN mote programming setup environment

Whenever a mote is plugged, the device path can be displayed by typing *motelist* on the shell. Output of that command was appended to another command for the installation such as

make telosb reinstall bsl, /dev/ttyUSB0

which installs the TinyOS application image on the mote plugged in USB0 port. If more than one motes will be programmed by the same application, different identities can be assigned by typing any number after "bsl,". The installation produces an output like the one below ensuring that the image was installed properly:

installing telosb binary using bsl tos-bsl --telosb -c 16 -r -e -l -p build/telosb/main.ihex.out MSP430 Bootstrap Loader Version: 1.39-telos-8 Mass Erase... Transmit default password ... Invoking BSL...

Transmit default password ... Current bootstrap loader version: 1.61 (Device ID: f16c) Changing baudrate to 38400 ... Program ... 2782 bytes programmed. Reset device ... rm -f build/telosb/main.exe.out-2 build/telosb/main.ihex.out

Blink application consists of a module and a configuration file, just as the other applications. The configuration file, BlinkAppC.nc has the following code:

```
configuration BlinkAppC {
}
implementation {
    components MainC, BlinkC, LedsC;
    components new TimerMilliC() as Timer0;
    components new TimerMilliC() as Timer1;
    components new TimerMilliC() as Timer2;
BlinkC -> MainC.Boot;
BlinkC.Timer0 -> Timer0;
BlinkC.Timer1 -> Timer1;
BlinkC.Timer2 -> Timer2;
```

BlinkC.Leds -> LedsC;

}

Under the implementation part, the other components are referenced. TimerMiliC() component is referenced three times to three different instances with the aliases of Timer0, Timer1 and Timer2. The rest of the configuration is about connecting the interfaces provided by the module component. The module component is given as below:

```
module BlinkC {
 uses interface Timer<TMilli> as Timer0;
 uses interface Timer<TMilli> as Timer1;
 uses interface Timer<TMilli> as Timer2;
 uses interface Leds;
 uses interface Boot;
}
implementation
{
 event void Boot.booted()
 {
  call Timer0.startPeriodic( 250 );
  call Timer1.startPeriodic( 500 );
  call Timer2.startPeriodic( 1000 );
 }
 event void Timer0.fired()
 {
  dbg("BlinkC", "Timer 0 fired @ %s.\n", sim_time_string());
  call Leds.led0Toggle();
 }
 event void Timer1.fired()
 {
  dbg("BlinkC", "Timer 1 fired @ %s \n", sim_time_string());
  call Leds.led1Toggle();
 }
 event void Timer2.fired()
 {
  dbg("BlinkC", "Timer 2 fired @ %s.\n", sim_time_string());
  call Leds.led2Toggle();
 }
}
```

The first part consists of declarations for the interfaces that the module provides such as Leds and Boot interfaces.

Immediately after installing the application, the mote boots by default and the interface Boot signals as directed by "event void Boot.booted()". That is the moment on which three different timers start to count up to 250, 500 and 1000 respectively. Whenever a cycle is completed, a timer fires the relevant LED. So that the three LEDs blink at 250, 500, and 1000 ms periods whenever the relevant timer fires for them, as stated in the module implementation. That blinkings can easily be determined by visual inspection.

Having been familiar with TinyOS basics, provided example applications in the TinyOS installation was investigated. The main radio interfaces are AMSend Receive provided SplitControl, and by ActiveMessageC, AMSenderC and AMReceiverC modules. They are used for the interconnection between an application and the message queue layer of the radio stack. It was found out that, under the folder /opt/tinvos-RssiBase XM1000/apps/tutorials/RssiDemo there exists the and SendingMote applications, which are convenient to use with some minor modifications for the purpose of the experiments.

3.1.4.1. SendingMote application

The configuration component of the application is given below:

#include "RssiDemoMessages.h"

configuration SendingMoteAppC {
} implementation {
 components ActiveMessageC, MainC;
 components new AMSenderC(AM_RSSIMSG) as RssiMsgSender;
 components new TimerMilliC() as SendTimer;

components SendingMoteC as App;

App.Boot -> MainC;

```
App.SendTimer -> SendTimer;
```

App.RssiMsgSend -> RssiMsgSender; App.RadioControl -> ActiveMessageC;
}

The modules ActiveMessageC, MainC, TimerMilliC and AMSenderC are referenced in the configuration and the interfaces provided by the corresponding module are wired to the interfaces of referenced components afterwards. The new instance of the main radio transmitter component, AMSenderC is aliased as RssiMsgSender.

The module component of SendingMote application is given below as

#include "ApplicationDefinitions.h"
#include "RssiDemoMessages.h"

module SendingMoteC { uses interface Boot; uses interface Timer<TMilli> as SendTimer;

uses interface AMSend as RssiMsgSend; uses interface SplitControl as RadioControl; } implementation {

message_t msg;

event void Boot.booted(){
 call RadioControl.start();

```
}
```

event void RadioControl.startDone(error_t result){
 call SendTimer.startPeriodic(SEND_INTERVAL_MS);
}

event void RadioControl.stopDone(error_t result){}

```
event void SendTimer.fired(){
    call RssiMsgSend.send(AM_BROADCAST_ADDR, &msg, sizeof(RssiMsg));
}
```

```
event void RssiMsgSend.sendDone(message_t *m, error_t error){}
}
```

In the implementation part, an instance to the built-in "message t" structure is created to be able to send a message by radio communication. The SplitControl interface, which is responsible to interconnect the application and the active message of the radio stack, is aliased as RadioControl. It is called whenever the mote is booted and if it can start without error, the timer of message sender is initiated being assigned а period of SEND_INTERVAL_MS constant. On each firing of the timer, a message is transmitted which is specified by the instance of message_t created before.

In the experiments, the message sending interval and message size parameters are points of interest. Message size is defined and can be modified in the included ApplicationDefinitions.h header in terms of milliseconds such as

```
enum {
   SEND_INTERVAL_MS = 250
};
```

```
#endif //APPLICATIONDEFINITIONS_H___
```

Various message parameters are defined in the message_t structure given as

typedef nx_struct message_t {
 nx_uint8_t header[sizeof(message_header_t)];
 nx_uint8_t data[TOSH_DATA_LENGTH];
 nx_uint8_t footer[sizeof(message_footer_t)];
 nx_uint8_t metadata[sizeof(message_metadata_t)];
} message_t;

The default message payload size is 28 bytes. But it can be configurable, for e.g. it can be set to 128 bytes by adding the line below into the corresponding Makefile in the application folder:

CFLAGS += -DTOSH_DATA_LENGTH=128

Other important parameters of interest are the communication channel and output power.

Due to the data sheet of CC2420, output power is controlled by TXCTRL.PA_LEVEL register and it is programmable at 8 different levels as stated by the table below:

PA_LEVEL	Output power [dBm]
31	0
27	-1
23	-3
19	-5
15	-7
11	-10
7	-15
3	-25

Table 2: Programmable output power levels of CC2420

To program the output power by TinyOS, a line similar to the one below below is added into the Makefile of SendingMote application, in which the assigned number corresponds to the PA_LEVEL in the table, so that, the line below sets the sending mote's output power to -15 dBm, after compiling the application.

CFLAGS += -DCC2420_DEF_RFPOWER=7

CC2420 motes are compliant to IEEE 802.15.4 specifications as stated before, which in turn makes it configurable to operate in 16 channels within the 2.4 GHz band, in 5 MHz steps. Due to the data sheet of CC2420 the RF frequency of channel k is given by the equation

$$F_{C} = 2405 + 5(k - 11)MHz$$
(11)

which replaces the right hand side of the equation in the line below added to the Makefile of both SendingMote and RSSIBase applications

so that both the transmitter and receivers operate in the same channel, which is 2450 MHz in this case.

3.1.4.2. RSSIBase application

RssiBase is the application that can be installed on a mote connected to the USB port and it can read the RSSI.

The configuration component is given below:

#include "RssiDemoMessages.h"
#include "message.h"

configuration RssiBaseAppC {
} implementation {
 components BaseStationC;

components RssiBaseC as App;

```
#ifdef __CC2420_H__
components CC2420ActiveMessageC;
App -> CC2420ActiveMessageC.CC2420Packet;
#elif defined(PLATFORM_IRIS)
components RF230ActiveMessageC;
App -> RF230ActiveMessageC.PacketRSSI;
#elif defined(PLATFORM_UCMINI)
components RFA1ActiveMessageC;
App -> RFA1ActiveMessageC.PacketRSSI;
#elif defined(TDA5250_MESSAGE_H)
components Tda5250ActiveMessageC;
App -> Tda5250ActiveMessageC.Tda5250Packet;
#endif
```

```
App-> BaseStationC.RadioIntercept[AM_RSSIMSG];
}
```

The module component of SendingMote application is given below as

```
#include "ApplicationDefinitions.h"
#include "RssiDemoMessages.h"
```

```
module RssiBaseC {
    uses interface Intercept as RssiMsgIntercept;
```

```
#ifdef __CC2420_H__
uses interface CC2420Packet;
#elif defined(TDA5250_MESSAGE_H)
uses interface Tda5250Packet;
#else
uses interface PacketField<uint8_t> as PacketRSSI;
#endif
} implementation {
```

```
uint16_t getRssi(message_t *msg);
```

```
event bool RssiMsgIntercept.forward(message_t *msg,
                                 void *payload,
                                 uint8_t len) {
  RssiMsg *rssiMsg = (RssiMsg*) payload;
  rssiMsg->rssi = getRssi(msg);
  return TRUE;
 }
#ifdef __CC2420_H__
 uint16_t getRssi(message_t *msg){
  return (uint16_t) call CC2420Packet.getRssi(msg);
}
#elif defined(CC1K_RADIO_MSG_H)
  uint16_t getRssi(message_t *msg){
  cc1000_metadata_t *md =(cc1000_metadata_t*) msg->metadata;
  return md->strength_or_preamble;
 }
#elif defined(PLATFORM_IRIS) || defined(PLATFORM_UCMINI)
 uint16_t getRssi(message_t *msg){
  if(call PacketRSSI.isSet(msg))
   return (uint16_t) call PacketRSSI.get(msg);
  else
   return 0xFFFF;
 }
#elif defined(TDA5250_MESSAGE_H)
 uint16_t getRssi(message_t *msg){
    return call Tda5250Packet.getSnr(msg);
 }
#else
 #error Radio chip not supported! This demo currently works only \
     for motes with CC1000, CC2420, RF230, RFA1 or TDA5250 radios.
#endif
}
```

It uses the InterceptBase component to forward the messages received from the radio but intercepts the RssiMsg and gets the RSSI value in it. For the CC2420 family, it gets the RSSI from the getRssi(message_t *) method of the CC2420Packet interface, which is provided by the CC2420ActiveMessageC HAL component.

Under the RSSIDEmo folder, there is a java folder which involver a java application called RssiDemo.java to display the RSSI values. To build it, "make" command is executed just once in that folder. Then, the RSSI readings can be displayed with the command:

java RssiDemo -comm serial@/dev/ttyUSB0:telosb

Since more than one transmitter motes are used, to distinguish between their readings, motes are assigned identities while installing the SendingMote application such as

make xm1000 reinstall,1 bsl,/dev/ttyUSB0

for mote id 1 and

make xm1000 reinstall,2 bsl,/dev/ttyUSB0

for mote id 2, so that the output look like:

... Rssi Message received from node 1: Rssi = -24 Rssi Message received from node 2: Rssi = -27 Rssi Message received from node 1: Rssi = -26 Rssi Message received from node 2: Rssi = -28 ..

Although the transmitters use the same channel, since their timers start on different random moments and they are configured to send fixed size packets

at specific intervals (due to the SendingMote program), there is no collision on the channel.

3.2. NI PXI

Those who are familiar with oscilloscopes know that they can display signal variations on time-domain. Although this is an important information, it can not display the full picture. Spectrum analysers provide the capability to analyze the signals in frequency domain. Since, in reality, most of the signals have complex components, viewing them separated into their frequency components makes it possible to measure much more parameters such as frequency, power, harmonic content, modulation, spurs, noise and so on.

There are simply two types of analysers: Fourier transform analysers and swept-tuned ones. The Fourier transform captures a time domain signal, digitizes it, samples it and performs some mathematics to convert it to the frequency domain. Because of its real-time analysis capability, a Fourier analyzer can capture transient signals in addition to the periodic ones.

Swept-tuned ones use heterodyne technique. The signal is first combined with a local oscillator through a mixer to be converted into an intermediate frequency (IF), then bandpass filtered imposed by the resolution bandwidth (RBW), and then converted to baseband by an envelope detector. It is projected to the display after digitized by an analog-to-digital converter and video filter.

The National Instruments platform belongs to the swept-tuned family. As stated in the data sheet of NI PXI-5661The equipment list is given below. Readers are referred to the web site of the vendor for more detailed technical specifications and data sheets.³

NI PXI-1042Q: It is the chassis in which the modular components are installed to create a measurement platform. It combines 8-slot PXI backplane which introduces a structural design optimized for use in a wide range of applications.

NI PXIe-8108 2.53 GHz Dual-Core PXI Express Embedded Controller: It is the main computing and controlling unit of the platform which integrates the I/O features. Window XP operating system was installed on it. It was connected to a screen so that it provides a user-friendly environment to configure and monitor the platform.

NI PXI-5610 RF Upconverter: That is the component responsible with upconverting the baseband signal.

NI PXI-5441 Arbitrary Waveform Generator with Onboard Signal Processing: It is a 100 MS/s arbitrary waveform generator with onboard signal processing.

NI 5600 RF Downconverter & NI PCI-5142 100 MS/s, 14-Bit Digitizer for Communications: The downconverter module and the digitizer together form the vector signal analyser component, which is named as NI PXI -5661 signal analyzer. It has got several advantages over traditional spectrum analysers. The most significant one, as stated in the data sheet, is throughput. Benchmarks show that there may be up to 7x improvements in spectrum sweep measurement performance and up to 200x improvement in power measurement performance compared to a traditional analyser.

The first step was to configure the platform as a spectrum analyser at 2.4 GHz. First of all, the interconnections between the waveform generator and upconverter as well as between the downconverter and the digitizer modules were done. Below is shown those interconnections.



Figure 2: NI PXI equipment with the modules interconnected

Next step was to install LabVIEW software on the XP operating system of the controller. LabVIEW is a graphical programming platform. That package contains the application development platform to create new virtual instruments (VI) or to modify the existing ones.

VIs are the LabVIEW programs, their appearance and functionality imitate physical instruments, such as oscilloscopes and multimeters. LabVIEW involves a wide range of sets of tools for acquiring, analyzing, displaying, and storing data.

In any VI, a user can create a front panel interface with controls and indicators. Controls are dials, knobs, push buttons and other input structures. Indicators are graphs, LEDs, and other structures to display output. After building front panel, structures can be added and modified to control the front panel objects. There are structures corresponding to traditional code structures such as "while-do", "if-then-else" and so on.

VIs can be in deep hierarchical structure, consisting of many subVIs. It provides the modularity and flexibility to modify the existing VIs or create new ones from them. SubVIs actually corresponds to functions in traditional codes.

The most important control on the panel is probably the resolution bandwidth setting. A spectrum analyzer's resolution presents its capability to resolve signals of equal amplitude. If the RBW is not sufficiently narrow, two different signals may be seen as a single one. Usually, they can only be resolved if the separation is greater than or equal to the 3-dB bandwidth of the selected RBW filter. However, making it narrower introduces a directly proportional decrease in sweep throughput. Another important control is the frequency range which is usually set together by configuring the centre frequency and frequency span. To test the equipment for the spectrum analysis of internally created signals, the RF output of the upconverter was connected to the RF input of the downconverter in order. Then, using the NI RF Vector Signal Analyzer Soft Front Panel and NI RF Signal Generator VI, a continuous wave signal was created with Quadrature Phase Shift Keying modulation at 2.4 GHz centre frequency and it was displayed successfully on the soft front panel at 10 KHz RBW.

4. IMPLEMENTATION & ANALYSIS of RESULTS

4.1. NI-PXI spectral measurements

The first step of the implementation was to configure one of the CC2420 motes in transmitter mode by installing the SendingMote application on it. It was configured to operate at 2450 MHz centre frequency and to send packets of 28 bytes default payload length at every one second.

A dipole antenna which was optimized for 2.4 GHz communication was connected to the RF input of the downconverter module of NI PXI. The distance between the antenna and the transmitting mote was set to 1 meter.

NI RF Vector Signal Analyzer (niRFSA) Soft Front Panel was configured to operate in Spectrum Mode. The centre frequency was set to 2.45 GHz, the frequency span was set to 10 MHz which is double the channel size and the resolution bandwidth was set to 10 kHz. However, no signal was displayed on the screen. Similar controls with another demo VI "named SMT Peak Search for niRFSA.vi" was also run to check if any signal peaks can be detected on the screen, but it neither worked.

Going on a further study of how swept-tuned spectrum analysers just like the NI PXI equipment work and how the SendingMote application makes the mote operate, showed that that is a normal situation. Because, the signal transmitted from the CC2420 mote is not a continuous wave. In that sense, it may be regarded as a transient signal. Transient signals are difficult to be phase locked by our type of vector signal analyzers. Although NI PXI-5661 introduces the capability of storing the waveforms in its memory, it is still limited in being able to analyze transient signals. Because, acquiring the signals and storing them and finally processing them is a serial process

which in turn makes the instrument to be usually unaware of the transient signals that arrive between those process cycles.

The idea of increasing the resolution bandwidth as much as possible and keeping the frequency span at minimum to decrease the time required per sweep did not help to overcome the problem.

If it was possible to somehow externally trigger the vector signal analyzer in a concurrent way with the transmitter, there could be a chance to phase lock the signal but during this study it couldn't be discovered any feature of the NI PXI to do it.

A swept-tuned spectrum analyzer with N sweeps per second requires wave pulses equal to or longer than 1000/N milliseconds for 100% probability of detection with full accuracy. In the data sheet of NI PXI-5661, an example benchmark is provided which implies that at 10 KHz RBW, 12 measurements/minute are performed. That means, it makes a sweep every 5 seconds or 0.2 sweep per second, which requires 1000/0.2 = 5000 milliseconds or 5 seconds pulses. Since the effective data rate of CC2420 is 250 kbps, it is required to create messages of payload length of 1250 Kbits, but that size is far beyond the maximum possible size that can be configured.

To configure the transmitter message size and issuing frequency in order to make it act like a continuous wave could be a solution to overcome the problem. Setting the message issuing frequency to 4 milliseconds and payload length to 128 byte which can be effectively transmitted in 128*8bits/250 kbps = 4 milliseconds, makes the messages imitating a continuous wave. This last solution worked and the signal could be displayed on the analyser's screen. But the spectral power was far less from the expected theoretical values by the order of 40 dBm. That excessive attenuation was thought to happen because of the antenna used on the input

of the downconverter, which unfortunately could not be replaced with alternative ones. Since then, validation attempts with NI PXI measurements were not carried on.

4.2. TinyOS RSSI measurements

At the beginning of the RSSI measurement via TinyOS applications, it was planned to set the output power of the transmitter motes at different configurable steps in order to have variety with respect to them. However, trials at -15 and -5 dBm levels failed to provide continuous or even any single RSSI readings after a few meters separation of transmitter and receiver, which in turn did not let any other alternative than programming them at 0 dBm throughout all the measurements.

As stated in the critical analysis section, measurements were taken along 20 λ tracks to mitigate the fast fading effects of multi-path components. Since a 2.4 GHz wave has a wave length of 0.125 meters assuming its speed same as the velocity of light in free space, 20 λ corresponds to 0.125*20 = 2.5 meters track length. Each track represents its middle point as the measurement location, i.e the distance between the transmitter and receiver. Each measurement track was implemented by placing the laptop on a sliding chair on which the base station mote is connected and moving the chair with a very slow walking velocity so that around 200 RSSI samples per transmitter mote per track were taken at 200 message/second message issuing frequency of the transmitter motes. Some of the histograms related to the distribution of the samples are provided in the next sub section which shows that the fading effect variations are indeed close to a uniform distribution along the track.

Averaging aforementioned distributions were implemented by taking the median of them instead of mean, because median is less sensitive to extreme values then mean, which were thought to help to get rid of unnatural samples at the beginning and at the end of the measurements caused by observer's hand starting and stopping the TinyOS application. However, the results introduced by mean and median did not introduce differences of more than 1 dB in general.

Throughout all the measurement scenarios, all of the transmitter antennas were aligned either the same straight line pointing the same direction or they were aligned on the same counter clockwise path pointing each other whereas the base station antenna was perpendicular with respect to that alignment.

Some photos taken from the measurement environment are provided in Appendix B. The Risk Assessment form filled to get permission to conduct experiments in Hendon Town Hall building is provide in Appendix C.

4.2.1. Scenario I: CC2420 practical antenna gain finding based on theoretical model

The first and simplest set of measurements was conducted in the short corridor of the Town Hall Building located in the first floor, consisting of a single transmitter mote and a base station. The red circle shown in the plan given below represents the transmitter mote, stuck on the wall at a height of 216 cm. whereas the blue diamond shape represents the 2.5 meters long measurement track by means of the base station mote at the height of 86 cm. The middle point of the track is 14.75 meters away from the transmitter. The door shown in the plan between the transmitter and receiver was kept open in the first subset of the measurements so there was not any obstacle on the direct line between the transmitter and receiver. Another subset of measurements was taken while the door was closed. Packet issue frequency of the transmitter mote was configured as 2000 milliseconds.



Figure 3: Scenario I layout

Below are two histograms of received power distributions in terms of picowatts, corresponding to the open and closed door cases respectively.



Figure 4: Scenario I open door RSSI readings distribution



Figure 5 Scenario I closed door RSSI readings distribution

According to (2), the partition dependent model of (10) takes the form of the path loss equation given as

$$L_P = L_0 + 20 \log(d) + \Sigma m_{\text{type}} w_{\text{type}} + X_{\sigma}$$
(12)

where L_0 represents the path loss with respect to 1 meter T-R separation and was calculated as 40 dB for 2.4 GHz.

Furthermore, for the open door measurements, (12) might be reduced by eliminating the third term in the right hand side of the equation, representing the non existing partitions in that case such as:

$$L_P = 40 + 20 \log(d) + X_\sigma$$
 (13)

Averaging the samples of open door measurements by means of calculating the median resulted in an average RSSI of -32 dBm. However, that value is read by the TinyOS application after the message was received. So that, the received power at the antenna is actually as less than that value as the antenna gain of the receiver which is given as being around 45 dB in the data sheet of CC2420.

Assuming the antenna gain being 45 dB, RSSI at the antenna is 45 dB less than -32 dBm which is equal to -77 dBm. Since the output power was configured at 0 dBm throughout all the measurements, the absolute of RSSI values found on the receiver antennas can be practically deemed as the path loss value in terms of dB, which leads to the path loss measured in the open door scenario as 77 dB.

The theoretical value of path loss with respect to (13) is some range around 63.37 dB with a few empirical standard deviations, where d = 14.75 meters.

Comparing the theoretical and the empirical values of 63.77 dB and 77 dB, the difference around 13 dB does not sound reasonable. Actually, in case of open door scenario, (13) is a simple free space path loss equation which was derived from Friis's Law, so that the aforementioned difference should be compensated by assuming the practical antenna gain of the receiver mote less. It was thought to be reasonable to assume that decrease as much as the difference, i.e. 13 dB.

According to that correction, antenna gain of the receiver mote was assumed as 45 - 13 = 32 dB throughout the rest of the experiments. So, the new empirical path loss finding for open door case is 64 dB at 14.75 meters.

Regarding the closed door case, the average RSSI was calculated as -35 dBm, which in turn makes the path loss 67 dB and the $\Sigma m_{type} w_{type}$ term in (12) equal to 3 dB. That term actually represents the door, which is heterogeneous in structure, composed of wooden and glass. The results are summarized in the table below.

Theoritical open door case path loss at 14.75 meters	63.77 dB + Χ _σ
Empirical open door case path loss at 14.75 meters	64 dB
Theoritical closed door case path loss at 14.75 meters	66.77 dB+ Χ _σ
Empirical closed door case path loss at 14.75 meters	67 dB
Empirical path loss of the door	3 dB

Table 3: Scenario I findings and results

4.2.2. Scenario II: Packet issue frequency

The second set of measurements was implemented again in the short corridor of the Town Hall Building, involving a single transmitter mote and a base station. Purpose of the experiment is to compare the RSSI readings with respect to 200 and 2000 milliseconds packet issuing frequency of the transmitter. The red circle and the blue diamond given below represents the same set of scenario I, however the base station mote was placed at a height of 116 cm and the middle point of the track was 8 meters away in this case. The door in between was kept open throughout the measurements.



Figure 6: Scenario II layout

Two histograms of distributions of received RSSI readings in terms of picowatts are given below, corresponding to the 200 ms and 2000 ms cases respectively.



Figure 7: Scenario II RSSI distribution at 200 ms packet issue frequency



Figure 8: Scenario II RSSI distribution at 2000 ms packet isuue frequency

The brief table given below summarizes the results

Table 4: Scenario II findings and results

Empirical 200 ms case path loss at 8 meters (dB)	-67
Empirical 2000 ms case path loss at 8 meters (dB)	-66

The theoretical value of path loss with respect to (13) is some range around minus 68 dB with a few empirical standard deviations, where d = 8 meters. There is no significant difference between the empirical findings and theoretical calculation. Furthermore, there is no significant difference of the findings of the two different message issuing frequency cases. However, since 200 ms case is slightly closer to the theoretical value, all the transmitters throughout the rest of the measurements were configured at 200 ms message issue frequency.

4.2.3. Scenario III: Measuring the observer effect

The third set of measurements, aiming to measure the observer effect, was conducted in the same corridor of scenarios I and II, consisting of two transmitter motes and a base station. The red circle shown in the plan given below represents the transmitter mote 1, whereas the pink circle represents transmitter mote 2, both stuck on the wall at the heights of 216 cm. The distance between two transmitters is 8 meters. The seven gray circles in between the two transmitters are the measurement points, each lined up at 1 meter separations. It should be noticed that, as opposed to the rest of the measurements, those are not measurement tracks but single points. Measurements were taken via a receiver located at the height of 116 cm, exactly at the same points with and without observer. To realize the case free of observer, the first and last 5 seconds periods of RSSI readings were trimmed to get rid of the observer leaving and entering the scene. On the other hand, to implement the case with observer, the observer just stood behind the chair on which the laptop was placed, to imitate the position while it is moved in the rest of measurements. The door shown in the plan between the transmitter and receiver was kept open during the measurements. Packet issue frequency of the transmitter mote was configured at 200 milliseconds.



Figure 9: Scenario III layout

Especially the first and last three seconds of the measurements may introduce significant differences up to 10 dB, probably due to the hands of the observer starting and stopping the TinyOS application on the laptop. So, the related counter parts in other experiments were decided to be removed, even though they were not supposed to affect the median average significantly.

As a result of the aforementioned trimmings, the RSSI measurement samples were observed to follow a steady pattern, as expected. The table below presents the difference of time averaged received powers of observer free case from those with observer at the antenna of the base station in terms of dBm.

	from mote1 (dBm)	from mote2 (dBm)
point1	2.357509	1.545176
point2	1.764134	-1.84573
point3	-9.13587	-3.78304
point4	-0.02701	-5.59542
point5	-6.95627	8.618909
point6	-3.37532	-0.58511
point7	1.931023	0.626584

Table 5: Scenario III time averaged received power differences

It is hard to conclude anything about the effects of observer; the differences given do not seem to follow a regular pattern. Those differences are thought to be due to different geometrical reflection structures caused by the observer at different points. However, it is assumed that, in track measurements, effects of multi paths caused by the observers are mitigated as well, since those differences are far less than enough to imply that the multi path components dominate the power received from the direct path signals. A related analysis may be referred in the critical analysis section of this study.

4.2.4. Scenario IV: Town Hall long corridor

The next scenario was implemented in the long corridor of the Town Hall Building located in the first floor consisting of four transmitter motes and a base station. The purpose of the scenario was to compare theoretical values to experimental findings and to measure the path loss of the door. The red, black, green and purple circles shown in the plan represent the transmitter motes number 1, 2, 3, and 4 respectively, all stuck on the wall at the heights of 216 cm and located along 8 meters of intervals. The blue diamond shapes represent 2.5 meters long measurement tracks with the base station of 86 cm height, similar to the previous legends. The middle point of any tracks is just in the middle of two neighbouring transmitters. The door shown in the plan between the first and second transmitters was kept open in the first subset of the measurements in order to eliminate any obstacles on the direct line between the transmitters and receiver. The other subset of measurements was taken with the door closed. Packet issue frequencies of the transmitter motes were set to 200 milliseconds.



Figure 10: Scenario IV layout

Below are presented two tables summarizing the path loss findings of the scenario of open and closed door cases, as well as providing the theoretical values based on (12) and (13). The experimental finding of 3 dB path loss of the same type of the door in scenario 1 was used in (12).

	Mote 1	Mote 2	Mote 3	Mote 4
Track 1 distance (meters)	4	4	12	20
Track 1 theoritical path loss (dB)	52 + Χ _σ	52 + Χ _σ	61.5 + Χ _σ	66 + Χ _σ
Track 1 experimental path loss (dB)	54	50	58.5	61
Track 2 distance (meters)	12	4	4	12
Track 2 theoritical path loss (dB)	61.5 + Χ _σ	52 + Χ _σ	52 + Χ _σ	61.5 + Χ _σ
Track 2 experimental path loss (dB)	72	53	48	62
Track 3 distance (meters)	20	12	4	4
Track 3 theoritical path loss (dB)	66 + Χ _σ	61.5 + Χ _σ	52 + Χ _σ	52 + Χ _σ
Track 3 experimental path loss (dB)	73	67	55.5	49.5

Table 6: Scenario IV open door case findings and results

	Mote 1	Mote 2	Mote 3	Mote 4
Track 1 distance (meters)	4	4	12	20
Track 1 theoritical path loss (dB)	55 + Χ _σ	55 + Χ _σ	64.5 + Χ _σ	69 + Χ _σ
Track 1 experimental path loss (dB)	52	52.5	66	70
Track 2 distance (meters)	12	4	4	12
Track 2 theoritical path loss (dB)	64.5 + X _σ	55 + Χ _σ	55 + Χ _σ	64.5 + X _σ
Track 2 experimental path loss (dB)	74	54	47	62
Track 3 distance (meters)	20	12	4	4
Track 3 theoritical path loss (dB)	66 + Χ _σ	61.5 + Χ _σ	52 + Χ _σ	52 + Χ _σ
Track 3 experimental path loss (dB)	79	66	56	48

Table 7: Scenario IV closed door case findings and results

The differences between the theoretical and experimental values in the open door case are usually up to 4 dB, which is thought to be reasonable. On the other hand, second and third track measurements with respect to mote 1 introduces differences in the order of 7-10 dB, which is probably caused by the frame the door that blocks the direct line between mote 1 and those tracks. It can be concluded that, that frame introduces a path loss of 3 to 6 dB.

In the closed door case, the differences between theoretical and experimental values follow a quite similar pattern with that of open door case, which is thought to be a validation of proper measurements. Furthermore, that similar pattern validates the experimental path loss finding of the door in scenario 1.

4.2.5. Scenario V: Town Hall Dual corridor

The previous scenario was modified by means of extending the layout to both of the corridors, consisting of two transmitter motes and a base station. The purpose of the scenario was also to compare theoretical values to experimental findings and to measure the path loss of the door and the walls in between. The red and black circles shown in the plan represent the transmitter motes number 1 and 2, both stuck on the walls of the long corridor at the heights of 216 cm and located along 8 meters apart from each other. Two measurement tracks were implemented, shown by the blue diamond shapes. Base station was kept at 86 cm height. The middle points of the tracks were located at 7.25 and 14.75 meters away from mote 1 along the short corridor, respectively. The door shown in the plan in the short corridor was kept open in the first subset of the measurements in order to eliminate any obstacles on the direct line between the transmitters and receiver. The other subset of measurements was taken with the door closed. The black lines represent the direct line between mote 2 and the tracks. Regarding the majority of track 1, the lines traverse 3 walls. Majority of track 2 introduces 4 walls. Packet issue frequencies of the transmitter motes were set to 200 milliseconds.



Figure 11: Scenario V layout

Two tables are given below, summarizing the path loss findings of the scenario of open and closed door cases, as well as presenting the theoretical values based on (12) and (13). The experimental finding of 3 dB path loss of

the same type of the door in scenario 1 was used in (12). The m_{type} term in (12) was taken as 3 in the theoretical calculation of path loss between mote 2 and track 1, whereas it was taken 4 with respect to mote 2 and track 2, representing the number of walls in between respectively.

	Mote 1	Mote 2		
Track 1 distance (meters)	7.25	10.76		
Track 1 theoritical path loss (dB)	57 + Χσ	$60.5 + 3w_{type} + X\sigma$		
Track 1 experimental path loss (dB)	50	64		
Track 2 distance (meters)	14.75	16.77		
Track 2 theoritical path loss (dB)	63.5 + Xσ	64.5 + $4w_{type}$ + X σ		
Track 2 experimental path loss (dB)	58	69		

Table 8: Scenario V open door case findings and results

	Mote 1	Mote 2
Track 1 distance (meters)	7.25	10.76
Track 1 theoritical path loss (dB)	60 + Χ _σ	$60.5 + 3w_{type} + X\sigma$
Track 1 experimental path loss (dB)	55	67
Track 2 distance (meters)	14.75	16.77
Track 2 theoritical path loss (dB)	66.5 + Χ _σ	64.5 + 4w _{type} + Χσ
Track 2 experimental path loss (dB)	63	75.5

Table 9: Scenario V closed door case findings and results

Regarding mote 1, the differences between the theoretical and experimental values are around 3 - 7 dB, which is thought to be reasonable. Looking at the two tracks, the differences of closed and open door cases constantly introduce a door path loss of 5 dB, which is close to the finding of 3 dB path loss in scenario 1. The 2 dB difference is probably due to the different segments of the door through which the signals traverse in those different scenarios. That is something expectable because the door is not homogenous in structure, upper part is made of glass where as the middle and lower parts are made of wooden.

Regarding mote 2, the first thing that is noticed is the difference of measurements in two cases, which actually should not be affected by the state of the door being either closed or not. That difference is thought to be caused by the people's movement in the rooms through which the black lines in the layout traverse. The smaller findings of open door case were assumed to be free of people intersecting the direct lines between. Analysing those findings, introducing one additional wall leads an increase of 5 dB from 64 to 69 dB. So that, it can be concluded that the experimental path loss of the aforementioned type of wall is 5 dB.

4.2.6. Scenario VI: Hatchcroft measurements

Last two sets of measurements were implemented in Middlesex University Hatchcroft Building first floor entrance space. Regarding the first set, the red, green and brown circles in the figure below represent transmitter motes 1, 2, and 3 where as the orange and blue lines represent track 1 and 2 respectively. All the transmitters and base station were located at the height of 50 cm. Motes 2 and 3 are separated from mote 1 by 9 and 4 meters respectively. Intersection of the tracks is 4.92 meters away from all the transmitters. Packet issue frequency was configured at 200 ms.



Figure 12: Scenario VI first set layout

The table given below presents the path loss findings of the layout above, together with the theoretical value based on (13).

	mote1	mote2	mote3
Track 1 empirical path loss (dB)	-46	-47.47	-45
Track 2 empirical path loss (dB)	k 2 empirical path loss (dB) -46		-44.47
Theoritical path loss at 4.92 meters	53 + Χ _σ		

Table 10: Scenario VI first set findings and results

The findings of two tracks are almost same which validates the accuracy of the measurements. Difference of path loss values between the motes may have probably been caused by the different antenna alignments with respect to the base station. The difference between the theoretical value and empirical findings of up to 8 dB is not so reasonable, which may have been due to some significant multipath components formed by the specific structure of the environment that could not be mitigated.

In the second set of the measurements, mote 3 was removed and a 1 mm wide plastic object was placed in front of mote 1 so that the direct line between mote 1 and base station traverses through the object. Only one track was taken as shown by the blue line in the figure below. Distance from the middle point of the track to both of the transmitters was 6.1 meters.



Figure 13: Scenario VI second set layout

The table given below presents the path loss findings of the layout above, providing also the theoretical values based on (12) and (13).

	Mote 1	Mote 2
Empirical path loss (dB)	46	47.47
Theoretical path loss at 6.1 meters	55.7 + (path loss of plastic object) + X_{σ}	55.7 + Χ _σ

Table 11: Scenario VI second set findings and results

The empirical findings are same with the previous case, which further validates the measurement accuracy. It may also be concluded that the plastic object does not introduce a significant path loss probably due to its thinness.

CONCLUSION

Modelling the path loss is essential to successfully design and deploy wireless communication networks in terms of signal coverage and power constrains.

Radio signals are subject to unpredictable effects of absorption, reflection, refraction, scattering and diffraction caused by objects such as walls, floors and other obstacles; so it is practically impossible to develop an accurate general analytical model for path loss. Moreover, it is quite difficult and tedious to accurately model a given specific environment due to the non-homogenous structural characteristics of aforementioned obstacles. Instead, it is more convenient to develop statistical models based on empirical measurements.

Several models have been developed by researchers to estimate path loss for indoor and outdoor wireless communications. Researchers began with the suggestion of an intuitive empirical model, which is a mathematical expression of the path loss dependent on distance and some other empirical parameters. They conducted measurements and used the results to find the parameters of their models. Then, comparing the measured results and the results offered by their models, they presented how closely their model represents the real environment.

The empirical model assuming the path loss as the summation of free space loss and the individual losses introduced by each partition of any kind of material lying on the direct line between the transmitter and receiver, is the most successful model in terms of estimation, which was validated to yield the least standard deviations in different kind of environments. The key point for indoor path loss studies is the elimination of small-scale fading by averaging the measurement results on a track of several wavelengths. Averaging via median introduces slightly better results because of its tendency to be less affected by extreme values. To ensure that the multi-path components reflecting from the walls do not dominate the received signal power, the transmission loss introduced by the material type of any obstacle should be around or less than 10 decibels, which is the common case for most of the usual objects in typical environments.

Experimental setup of the NI PXI equipment introduced several challenges. The signal transmitted from the CC2420 mote is not a continuous wave and that transient type of signals are not likely to be phase locked by swept tuned signal analyzers. Because, acquiring the signals and storing them and finally processing them is a serial process which in turn makes the instrument to be usually unaware of the transient signals that arrive between those process cycles. After several attempts to overcome the challenge, configuring the transmitter message size and issuing frequency in order to make it imitating a continuous wave worked. However, the excessive attenuation, probably due to inconvenient input antenna, prevented the spectral measurements to carry on.

Histograms related to the distribution of RSSI readings via TinyOS show that the fading effect variations are indeed close to uniform distributions along the measurement tracks, which validates the multi-path power component mitigation technique. The variations from median values are far less than enough to imply that the power received from the multi path signals can dominate the direct path components.

According to the first scenario of measurements, it was concluded that the significant theoretical and the empirical path loss difference should be

compensated by assuming the practical antenna gain of the receiver mote less than the value proposed in the related data sheet by that difference.

There is no significant difference of programming the transmitter motes whether at 200 or 2000 ms. packet issue frequency, but slightly more realistic results at 200 ms.

The third scenario shows that it is hard to conclude anything about the effects of observer; the differences given do not seem to follow a regular pattern. Those differences are thought to be due to different geometrical reflection structures caused by the observer at different points.

Throughout the other scenarios, the differences between the theoretical and experimental values were reasonable. Some of the experiments also cross validated their results. Designers/researchers who want to use the theoretical model in question, lack longer or more detailed tables of path loss values with respect to various material types. An extension of this study involving providing that will be a useful future work.

APPENDIX A: TINYOS INSTALLATION

VMWARE Player was installed on the author's laptop's Windows 7 operating system, followed by downloading and using an Ubuntu Linux 10.04 version image to be played by VMWARE. The repository list file of Ubuntu was updated by adding the address of TinyOS community repository source for the related version:

deb http://tinyos.stanford.edu/tinyos/dists/ubuntu lucid main

TinyOS was installed by the use of the command given below:

sudo apt-get update sudo apt-get install tinyos sudo apt-get install tinyos-2.1.1

To install the latest support for telosb based products, to which actually CC2420 belongs, following commands were executed:

cd /opt

sudo svn checkout http://tinyos-main.googlecode.com/svn/trunk/ tinyos-main-read-only sudo cp -R /opt/tinyos-main-read-only /opt/tinyos-2.x

To make sure that the TinyOS root is used whenever a terminal is opened and a program is compiled, the commands below were executed:

sudo cp /opt/tinyos-2.1.1/tinyos.sh /opt/tinyos-2.x/tinyos.sh sudo chmod +x /opt/tinyos-2.x/tinyos.sh sudo gedit /opt/tinyos-2.x/tinyos.sh

The last command edits the tinyos.sh file in which the environment variables were set as given below:

echo "Setting up for TinyOS 2.x Repository Version" export TOSROOT= export TOSDIR= export MAKERULES= TOSROOT="/opt/tinyos-2.x" TOSDIR="\$TOSROOT/tos" CLASSPATH=\$CLASSPATH:\$TOSROOT/support/sdk/java:..:\$TOSROOT/support/sdk/java/ti nyos.jar MAKERULES="\$TOSROOT/support/make/Makerules" export TOSROOT export TOSDIR export TOSDIR export CLASSPATH export MAKERULES

To shift the default folder for the TinyOS root path from the original version to the updated version, the related line in the file /.bashrc

source /opt/tinyos-2.1.1/tinyos.sh

was replaced with that one:

source /opt/tinyos-2.x/tinyos.sh

Finally, the installation as well as the communication with motes were tested via a simple test application called Blink. It simply blinks the 3 mote LEDs. It actually tests if the boot sequence and millisecond timers are working properly.

APPENDIX B: PHOTOS









APPENDIX C: RISK ASSESSESMENT FORM⁴

Risk Assessment

Risk Assessment For: Town Hall Experiment: Air	Date: 24/7/2013
Monitoring	
Carried out by: Purav Shah	Review Date: if changes are made to experiment and equipment used.

Hazard	Persons affected	Risk Controls	Risk Rating		Accept Risk	
		Outline the controls in place	Severity	Likelihood	Risk	Yes/no
Trip hazard caused by use of extension power cable to supply Pc trolley placed at various locations along 1 st floor Town Hall corridor between room numbers. The equipment will be used for a two week period to monitor the air by using wireless sensors fixed to the walls.	Staff, students and visitors	Power cable to be trailed along wall skirting and taped in position to avoid trailing on open floor and hang over door ways to avoid trip hazard. PC to be positioned in corridor so as not to present an obstruction or trip hazard to pedestrians. Layout of trolley and cable to be inspected by academic supervisor daily.	2	1	2	Yes

⁴ Only the first page is provided

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