Mitigating Multipath Fading Through Channel Hopping in Wireless Sensor Networks

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Abstract—Wireless communication between a pair of nodes can suffer from self interference arising from multipath propagation reflecting off obstacles in the environment. In the event of a deep fade, caused by destructive interference, no signal power is seen at the receiver, and so communication fails. Multipath fading can be overcome by shifting the location of one node, or by switching the communication carrier frequency. The effects of such actions can be characterized by the coherence length ($L$) and coherence bandwidth ($B$), respectively, given as the amount of shift necessary to transition from a deep fade to a region of average signal strength. Experimental results for a representative 2.4GHz wireless link indicate $L = 5.5\text{cm}$ and $B$ can vary from 5MHz at long ranges up to 15MHz for short links. For wireless sensor networks (WSNs), typically operating under the IEEE802.15.4 standard, multipath effects are therefore best handled by a channel hopping scheme in which successive communication attempts are widely spread across available carrier frequencies.

I. INTRODUCTION

In an indoor environment, every wall, person, and piece of furniture acts as a reflector for RF signals. As a result, on top of the signal following the direct line-of-sight (LOS) path, a node receives multiple echoes which have bounced off nearby elements. Because the paths those echoes follow are necessarily longer than the LOS path, they arrive later, typically with several $\text{ns}$ delay. This is an unwanted phenomenon, particularly in narrowband communication. If the different signals are phased appropriately, they can destructively interfere, and the receiver will be unable to decode the signal even when physically close to the transmitter.

In Fig. 1, we show the effects of such multipath fading (the experimental details will be presented in Section III). This figure shows how the packet delivery ratio (PDR, the ratio of number of received to sent packets; $0 \leq \text{PDR} \leq 1$) varies as only the position of the transmitter changes. While in most locations reception is good (i.e. PDR $> 0.9$), multipath fading causes the PDR to drop to 0 in certain locations, called deep fades.

Multipath fading is a well known phenomenon, and depends strongly on the communication carrier frequency. It is often combated (such as in IEEE802.15.1, Bluetooth) through channel hopping, a Medium Access Control (MAC) layer scheme wherein the nodes’ radios constantly "hop" among different frequency channels. In IEEE802.11b the desired signal is spread across a wide bandwidth to avoid narrow bandwidth fading, and this direct sequence technique is a physical layer approach to defeating narrowband fading.

Channel hopping has been somewhat overlooked in WSNs as the vast majority of MAC protocols are single channel. The widespread adoption of IEEE802.15.4 radios capable of rapidly switching between multiple channels opens the possibility for exploiting channel hopping in WSNs. The goal of this paper is to present the reader with experimental results gathered in a number of scenarios, and to use this data to discuss how a channel hopping MAC protocol can efficiently fight multipath fading in the context of WSNs. By mitigating the impact of multipath fading, individual links and the network as a whole becomes more reliable; network power consumption is lowered as energy is no longer wasted in inefficient retransmissions along lossy links.

Several papers have studied the relationship between an environment and coherence length and bandwidth [2], [9], [10], and this paper is intended to add to this body of knowledge, while being aimed at the wireless sensor network implementer rather than the communication theorist. To that end, we propose a non-conventional approach to characterizing channel coherence$^1$ that uses motes like those used in today’s deployments, and we provide design parameters of interest to the WSN engineer. It is known that the coherence

$^1$We actually measure the change required to see a significant difference in channel conditions.
bandwidth is smaller for long range links than for short range links (outdoors compared to indoors). [2] states that coherence bandwidth is independent of distance, but the results presented in [2] actually shows that for very short links (less than a few meters) there is a clear relationship between coherence bandwidth and link length. We show this effect as well, and place it into perspective for WSN deployments. This work presents a practical look at channel characteristics, the impact of multipath on WSN radio links, and how frequency and/or spatial diversity improve link reliability.

We start by giving the reader the necessary background on multipath fading in Section II. Section III presents the experimental setup and the collected data, from which Section IV extracts the coherence length and coherence bandwidth. We use these results in Section V to discuss how channel hopping can alleviate multipath fading.

II. MULTIPATH FADEING AND CHANNEL HOPPING

A. Multipath Fading

Cluttered environments result in more echoes, and larger numbers of potential signal paths. Although multipath propagation is a characteristic of almost all wireless links, it is particularly problematic in indoor environments such as offices, which feature large objects such as desks and cabinets, and relatively short path lengths. If the exact location and nature of all the elements are known, relatively simple techniques can be applied to determine whether multipath fading occurs at any given spot. Unfortunately, not only are these characteristics hard to infer, but the environment keeps changing as people and equipment move and doors open and close. From a practical perspective, multipath fading is unpredictable and is treated as a probabilistic phenomenon in communication theory.

Note that in a typical office environment, different RF technologies such as IEEE802.15.1 (“ZigBee”) and IEEE802.11 (WiFi) coexist and can cause external interference. In this paper, we focus only on multipath fading by running our experiments in an environment free of WiFi interference. The interested reader in referred to [1] which evaluates the impact of IEEE802.11 interference on WSNs.

To better understand multipath fading, consider the simple situation shown in Fig. 2, where a fixed node A attempts to communicate with a mobile node B in the presence of a LOS path, $p_1$, and a single reflection, $p_2$. We also assume that there is no attenuation to the signal due to path length or reflection, in order to further simplify the analysis. The two paths add together to generate the received signal at B, $r_B$, expressed in (1).

$$r_B = \cos \left( 2\pi f t + \frac{2\pi x}{\lambda} + \phi \right)$$  \hspace{1cm} (1)

where $f$ is the carrier frequency, $t$ is time, $\lambda$ is the wavelength of the RF signal, and $\phi$ is the phase shift incurred by the reflection (which we will assume to be 0). Multipath fading occurs when the phase relationship of these two signals results in a signal with very small amplitude, and it is important to consider how the parameters of carrier frequency and changes in $x$ impact this amplitude. The amplitude of this sum is given in (2).

$$A_{r_B} = \cos \left( 2\pi \left( \frac{l}{\lambda} - \frac{x}{\lambda} \right) \right)$$  \hspace{1cm} (2)

Changing either the distance $x$ or the carrier frequency $f$ (where $\lambda = c/f$, $c$ being the speed of light) results in periodic changes in received signal amplitude. We are interested in understanding what sort of change in the argument will result in very different channel conditions, and a change of $\pi/2$ results in the amplitude changing from maximum to 0.

In wireless communication theory, the concept of coherence length and coherence bandwidth are used to quantify the maximum change in distance or frequency that will result in the channel being largely the same (highly correlated). We adopt these terms because they are highly related to the quantities of interest, but we instead consider the change in location or frequency required to see a significant change in the channel with high probability.

Typically, the coherence length is given in terms of a coherence time where these two values are related by an average velocity of the communicating nodes or objects in the environment. Coherence length is more instructive to WSNs, however, because the nodes are often static and situated in slowly varying environments.

Solving for the required change in $x$ and $f$ yields bounds for the coherence length, $L$, and the coherence bandwidth, $B$, expressed in (3).

$$\left\{ \begin{array}{l} L = \lambda/4 \\ B = \frac{c}{4\pi f^2} \end{array} \right.$$  \hspace{1cm} (3)

One interesting result is that $L$ depends entirely on $\lambda$ (or carrier frequency $f$) while $B$ depends entirely on the environment, and specifically the difference in the arrival times of the two paths. In practice, $L$ does depend on geometry, and (3) gives a lower bound for $L$; typical values for $L$ are less than $\lambda$. $B$ is usually specified in terms of the root-mean-square delay spread [2], which is a weighted measure of the interpath length difference divided by the propagation speed. The expression for $B$ can be expressed in these terms by substituting the standard deviation of a Bernoulli trial in for the path length difference:

$$B = \frac{1}{2 \cdot \sigma_{\tau}}$$  \hspace{1cm} (4)

We expect that the larger the separation between nodes, the larger the interpath spacing will be, resulting in a smaller coherence bandwidth. Conversely, at short ranges, we expect a longer coherence bandwidth. The channel delay spread ranges from a few ns to 100’s of ns indoors. For a typical case with IEEE802.15.4 in the 2.4GHz ISM band and operating indoors, we expect $L \approx 3cm - 10cm$ and $B \approx 100MHz - 1MHz$. 

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TMIE. This technique is used to increase robustness by combating external interference and persistent multipath fading. It is implemented in technologies such as IEEE802.15.1, adopted by the Bluetooth consortium. In IEEE802.15.1, the physical layer features 79 1-MHz wide channels in the 2.4GHz ISM band. Devices wishing to communicate group around a leader and synchronize to that leader’s clock. Time is sliced up into $625\mu s$-long slots; a hashing function translates the leader’s address into a channel hopping pattern. All nodes follow that preset pattern, changing channels 1600 times per second.

IEEE802.15.4 [3] is the de-facto standard for low power radios used in WSNs. In the 2.4GHz band, it allows communication over 16 frequency channels. A mandated turnaround time of lower than $192\mu s$ enables efficient channel hopping protocols.

The appearance of IEEE802.15.4 compliant radios made it possible for WSNs to exploit channel hopping. Time Synchronized Mesh Protocol (TSMP) [4] was the first commercial solution to do so. [5] presents experimental results in which 44 nodes run TSMP for 28 days in a printing facility, achieving an end-to-end delivery ratio of 99.999%. This technology is since being adopted by standardization bodies such as HART (in its wireless extension WirelessHART [6]), the ISA100 Wireless Compliance Institute (in ISA100a [7]), and more recently the workgroup IEEE802.15.4e (in their latest proposal [8]).

### III. Experimental Setup

We want to evaluate, in an otherwise constant environment, the packet delivery ratio (PDR) of a single link connecting a transmitter and a receiver (1) for different relative positions and (2) for each of the 16 available frequencies.

The PDR is obtained by having the transmitter send a burst of 1000 packets, and by counting the number of packets successfully decoded by the receiver. We use two eZ430-RF2500 motes (MSP microcontroller and CC2500 radio)\(^2\), with the transmitter mounted onto a Protomat 91s PCB board prototyping machine. This prototyper features a mobile arm capable of moving inside a $20cm \times 34cm$ area in $1cm$ steps, the movement of which can be programmed through a serial connection.

A computer is connected to the (fixed) receiver and the prototyper. At the beginning of a measurement (represented in Fig. 3), the arm of the prototyper is moved to the wanted location, which takes $1s$. The receiver then transmits a start command to the transmitter, indicating the channel to be used. To ensure that this command is received, it is sent ten times in a row, on channel 26 (which lies outside of the IEEE802.11 channels) and maximum power (1dBm). Upon receiving a start command, the transmitter transmits 1000 29-byte-long packets at the requested frequency. The PDR is determined by the receiver, and stored on the computer. Each of the 1000 packets take $2.3ms$ to be send; one measurement (including the movement of the arm) takes $4s$.

During one complete cycle, the arm moves through a regular grid of step $1cm$, covering 735 locations. This cycle is repeated for each of the 16 IEEE802.15.4 frequencies. One complete experiment takes 13 hours, and is carried out at night, in the absence of people and IEEE802.11 traffic. The floor plan of

\(^2\)As an online addition to this paper, the open-source firmware can be downloaded at http://cnx.org/content/col10684/latest/.
IV. COHERENCE LENGTH, COHERENCE BANDWIDTH

When in a deep fade, a node can move locations or change the frequency it communicates on, until it obtains a “good” link. In our experiment, we consider a link to be “good” when it features a PDR equal to or greater than the averaged PDR from the same data set (averaged over all 16 frequencies and all 735 locations, at a given frequency). We call a deep fade a location where PDR<5%; there are 30 - 100 deep fades in a given data set.

Our analysis goes as follows. When in a deep fade, we compute how far the mote has to be moved (in either x - y direction) until it features a good link. We call this value coherence length, averaged over all deep fades in the data set. Similarly, we call coherence bandwidth the frequency shift a link has to undergo to transition between deep fade and “good” link.

the measurement location is shown in Fig. 4. The experiment is repeated three successive nights, for different locations of transmitter and receiver. We obtain data sets for settings where the link between transmitter and receiver is short with LOS (T1 → R1), medium far with LOS (T2 → R1) and medium far without LOS (T3 → R2). For easier reference, we call the resulting data sets short, medium and long, respectively.

Each of the short, medium and long data sets is composed of 16 graphs similar to Fig. 1, one for each of the IEEE802.15.4 frequencies. All indicate that the link is good (PDR > 90%) at the majority of locations, with regions of deep fade due to multipath interference. Qualitatively, when transmitter and receiver are close, deep fade areas form extended “valleys” (as in Fig. 1), whereas they become more localized as the motes are separated by more distance. Similarly, when comparing results across different channels, the closer the motes are, the less variance there is between results for adjacent channels. We quantify these observations in Section IV through coherence length and coherence bandwidth.

V. MULTIPATH FADING AND CHANNEL HOPPING

The previous section suggest that, in the “short” and “medium” cases, the hopping pattern should be set such that the successive channels are separated by multiple frequency channels, i.e. a random hopping pattern is not sufficient. In the “long” case, however, this is not necessary. The underlying assumption is that channel hopping is coupled with a retransmission policy, such that, when a packet does not get through, changing the channel should ensure that it does at the next attempt.

We use the 48-node office network deployed in UC Berkeley...
and presented in [1] as a representative real-world office deployment, the topology of which is presented in the upper part of Fig. 7. The lower part shows the cumulative distribution function (CDF) of the link lengths. It indicates that while only 5% of the links pertain to the “short” category, 88% qualify as “long” links.

As a result, in the majority of the cases, a pseudo-random hopping pattern in which a jump can be made to a possibly adjacent channel provides enough robustness against multipath fading. Occasionally, however, this will not be enough, and the hopping pattern should be designed in such a way that successive channel are separated by 25MHz channels or more.

These observations allow us to propose the hopping pattern presented in (5), where 5% of the links are shorter than 3m, 88% of the links are longer than 5m, and while only 5% of the links pertain to the “short” category, 88% qualify as “long” links.

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