Rethinking Indoor Wireless:
Low Power, Low Frequency, Full-duplex

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1. INTRODUCTION

One of the largest market segments for wireless are indoor wireless networks (e.g. home networks and enterprise networks). In such networks connectivity is limited both by physical obstacles and structural barriers such as walls, and by interference in the wireless spectrum. The most commonly used ISM bands for WiFi networks are at 2.5 GHz and 5 GHz, and the signals at such high frequencies do not easily pass through the obstacles.

To increase connectivity and extend coverage, WiFi networks use large transmission powers, typically up to 100 mW. This gives connectivity of a few tens of meters, even through walls. At the same time, line-of-sight connectivity may reach significantly greater distances, causing far away nodes to interfere in very unusual patterns. All this makes indoor WiFi networks very difficult to plan and deploy [1, 2].

The unusual and asymmetric connectivity graph has particularly detrimental effects for MAC design. The uneven wireless signal propagation causes hidden-terminal problems, when a source and a destination of a link are not able to sense the same interfering nodes. These problems can be resolved by careful measurements and frequency planning [1, 2], but this increases the deployment complexity and cost, and may not be viable for many small environments, such as home and small office networks. Long distance interference also decreases spatial reuse.

We argue that the existing WiFi networks are ill-suited for indoor wireless networks. Instead, we propose a novel wireless design paradigm. Firstly, indoor wireless networks should use lower carrier frequencies. Instead of the current WiFi ISM bands, we suggest the use of TV bands. The FCC has recently approved the unlicensed use of white spaces, below 900 MHz, formerly used by analogue TV channels. It is well known (and we substantiate it in Section 2) that the penetration of signals increases as the frequency drops. Using frequencies below 900 MHz can significantly improve connectivity in an indoor environment. Low frequencies also exhibit more uniform signal propagation, which simplifies the network design and deployment problems.

Secondly, since the penetration is improved by decreasing the carrier frequency, we can in turn decrease the transmission power, and keep the same connectivity as in a WiFi counterpart. We propose to use transmission power 100 times - using a transmission power of 0.5mW at 530MHz we can establish a similar connectivity pattern as a 50mW WiFi network at 5 GHz (see Section 3). The other obvious benefit of lower transmission power is lower power consumption.

Thirdly, due to low carrier frequency and improved propagation, we can implement advanced signal processing and antenna design techniques to cancel the self-interference and achieve full-duplex communication in a single band in realistic indoor scenarios. The benefits of full-duplex are twofold: (i) a node that is sending a packet is able to receive a packet at the same time in the same band, potentially doubling the throughput, and (ii) we make carrier sensing "work": it is made symmetric and hence we can eliminate the remaining hidden terminal problems. We discuss the feasibility of full duplex and its performance benefits in Section 4.

2. SHORTCOMINGS OF EXISTING WIFI

We now expand on the shortcomings of current WiFi design.

2.1 Attenuation and Path Loss

It is well known that lower frequencies propagate further. The path loss of an electro-magnetic wave at ISM frequencies in free-space (or line-of-sight) increases linearly with the logarithm of the signal carrier frequency [3]. Furthermore, the reflection and absorption in different dielectric materials vary with the frequency, and high frequency signals propagate less through obstacles such as walls and doors. For example, [4] shows that the indoor attenuation of a 1900 MHz signal is up to 13 dB higher than the attenuation of a 900 MHz signal. Motley and Keenan [5] demonstrate that the indoor radio coverage at 1700 MHz is significantly less than at 900 MHz, and as a consequence the link ranges can be halved. For these reasons most of the current research in cognitive radio considers TV bands as the prime frequencies (see e.g. [6]).

2.2 Non-uniform Coverage

The uneven signal propagation implies uneven connectivity in an indoor network. Wireless nodes a short distance apart but separated by several walls or doors may not connect, while nodes can connect to far-away nodes that are on a line-of-sight (or separated by semi-transparent barriers such as glass). Indeed, several empirical studies have reported a large variation in the received SNR as a function of link length in a WiFi network (see for example [2, 7]). WiFi typically uses high transmission power ($\approx$ 100 mW) to overcome these limitations and guarantee reasonable coverage in worst case scenarios.

As an example, we also observed significant heterogeneity in the propagation pattern for our own office network. We measured the connectivity between nodes placed at different locations, shown in Figure 1. We used 802.11a network cards based on Atheros AR5212 chipset (Dlink DWL AG530 and Netgear WAG311). The transmission power was 50 mW and the carrier frequency around 5 GHz (we don't use 802.11b/g network since it interferes with our enterprise WiFi network). Each node broadcasts 1000 packets of 50B at all available rates and we kept statistics of the received packets.

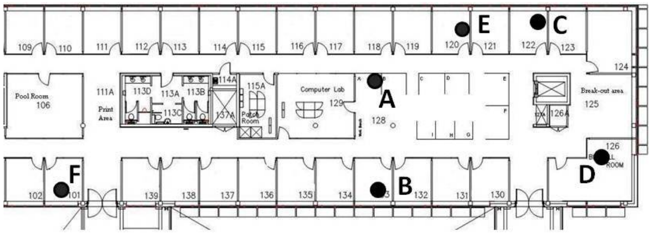

Figure 1: Floorplan of our office with measurement locations (95m × 18m). The area left of A is an open floor office area. Above and below are regular offices. Most of the obstacles are glass, wood or concrete. The only exception is the elevator, lying in between C and D, which has a tick concrete and metal case.

We recorded the highest rate for each link in either direction for which the destination receives at least 80% of the packets of size 50B[1]. The achieved rates and the approximate corresponding SNRs are shown as the solid line in Figure 2.

For a perfectly uniform propagation pattern, path loss depends only on the link lengths through the following relationship

$$\text{path loss} = b \cdot \text{link length}^{-\alpha}. \tag{1}$$

Hence path-loss and link-length would be linearly related in a Log-Log plot (the line in Figure 2 should be straight). Instead, we observe that there is a large fluctuation in channel quality as a function of distance. For example, from Figures 1 and 2 we see that link C-E is a short link, but traverses two walls and has a lower link quality than Link A-B, which is longer but traverses a single wall. Link B-C happens to be completely disconnected whereas a longer link, A-D is connected. All this is because of different obstacles lying on the paths.

2.3 Interference and Network Design

The heterogeneous signal propagation patterns poses significant challenges for wireless network design. For the topology of Figure 1, we found that node A could connect to node F but that node B could not connect to node F, even though the distance from A to F and from B to F are almost identical. Hence node F is a hidden terminal for node B when it sends data to A (when F transmits, it will seriously hamper the performance of link A-B).

However, node F has no need to connect to node A. In a typical WiFi deployment, Access Points (APs) are dense and relatively close to the nodes [1], in order to maintain high SNR for each link. In such a setting long-distant links are undesirable. They are not used for data transfer and only cause interference, leading to inefficiency [9] and hidden terminals. Similarly, in most mesh networks long links are usually not desirable.

A home user wants to connect to their own AP, and not to the AP of a neighbour that happens to have a line-of-sight connectivity through a window. Long-distance links also pose greater security risks (e.g. through wardriving). Therefore from the network design and deployment perspective, uniform signal propagation and uniform connectivity are desirable objectives. Several approaches have been developed to achieve this goal in WiFi, for example distributed power control algorithms [10], intelligent frequency allocation [1], or both [2].

2.4 Battery lifetime

High transmission power drains batteries in mobile devices. The number of devices that are battery dependent is growing (e.g. mobile phones, netbooks etc), and many are frequently connected to indoor wireless networks. Currently, turning on WiFi on a mobile phone decreases its battery life time by a factor of 3 to 4. The actual transmit power can be a considerable fraction of the circuit consumption. The power consumption of an 802.11 chipset reported in [11] is 400 mW when transmitting at 100 mW and 45mW in power-saving mode.

3. LOW IS LOVELY

We propose a different design paradigm for indoor wireless networks, using Low Frequency and Low Power. We recommend that indoor wireless network should use white spaces (the vacant analogue TV bands, between 470 MHz and 806 MHz) and 100 times less transmit power than WiFi (or ≈1 mW). In this section we discuss the performance and benefits of such a network. We argue that the indoor coverage at white space frequencies is larger than that of a WiFi network and as a consequence we can decrease the transmit power. We also demonstrate that the signal has a more uniform propagation. As a by-product of the increased propagation, we can use full duplex, as we discuss in Section 4.

3.1 Extended Coverage

We described signal propagation measurements for 802.11 in Section 2.2. To measure the propagation in white space we used the Lyrtech Small-Form Factor Software Defined Radio (SDR) platform. The radio board operates in TV band frequencies, and has a single radio with separate transmission and reception circuits, each with its own antenna. The two antennas are approximately 10 cm apart. The radio module operates with 20 MHz bandwidth. It uses a fixed transmission power roughly equal to 0.5mW.

We positioned a sender and a receiver at different lo-

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[1] We were not able to extract the SNR at the receiver from these measurements; instead, we use the measurements from [8] to estimate the approximate SNR needed to achieve these rates.

cations as shown in Figure 1. Signals were transmitted at 0.5 mW at 530 MHz and we measured the SNR at the receiver[2]. We also verified the link connectivity using our implementation of 802.11b-like PHY for Lyrtech platform (2 Mbps QPSK) and observed good connectivity for SNR greater than 10dB. We transmitted several packets over each link and recorded the received SNR for each packet. We plot the average achieved SNR with confidence intervals and the corresponding data rates in Figure 2, where the dashed line connects the average SNR for each link.

We compare the average SNRs for the 802.11a network and the Low Power, Low Frequency network. In some cases, the links in the Low Power, Low Frequency network have better average quality than the WiFi counterparts (links C-E, A-E, A-C, B-C). In other cases WiFi has a better quality, by up to 2 dB - 5 dB. In summary, we observe that up to link lengths of about 40m, the coverage and the link qualities are comparable to the ones of the 802.11a network.

3.2 Uniform Propagation

We now explore the homogeneity of the propagation pattern. As explained in Section 1, a uniform propagation pattern should yield a straight line in Figure 2. From the figure we conclude that the connectivity in white space is much more uniform and closer to a straight line than at 5 GHz. The only exception is the link C-D. For this link, the signal is heavily absorbed and reflected by concrete and metal of the elevator located in between nodes C and D.

We also see that there is a long-distance line-of-sight link A-F that is present in WiFi but which does not exist in the white space. This is because A cannot connect to F in the white space due to low transmit power. Again, this is beneficial for the network design since long links introduce unnecessary interference and hidden terminals, and reduce spatial reuse.

4. FULL-DUPLEX IN SINGLE BAND

Transmissions to and from a node in a single band interfere, hence a simultaneous transmission and reception at a node requires several orthogonal channels. We propose two techniques that allow both transmissions on the *same* channel in realistic indoor scenarios. This offers a potential double gain in the throughput. Our reference hardware implementation is described in Section 3.1.

In order to enable full duplex, we need to eliminate the *self-interference*, the interference at the receiver coming from our own transmission. The first technique we propose is based on interference cancellation. The second technique relies on the use of a nulling transmit antenna, an antenna that forms a signal propagation pattern which is almost omni-directional, except for one particular direction where the received signal is very weak. We discuss these techniques in Sections 4.1 and 4.2. We envisage combining them in a future system implementation.

Removing self-interference is never perfect and leaves some residual noise whose power is proportional to the power of the self-interfering signals. In order to decode the packet successfully, the remaining self-interference has to have much less power than the useful signal. We show in Section 4.3 that this is indeed possible in the Low Power, Low Frequency network, where the signal attenuation due to propagation is low (as it is in white spaces) and link lengths are “reasonable”, i.e. not more than 10m-20m, typical of most home and small enterprise networks. Full duplex does not work with existing WiFi: the higher frequency means that the nodes would have to be very close together (less than 1 meter) for the full-duplex to work. We discuss network design issues for full duplex in Section 4.4.

4.1 Analogue Interference Cancellation

Multi-user detection and interference cancellation techniques have been widely used in digital communication systems (see e.g. [12]). However, there are two important aspects to consider when implementing them in our system. Firstly, the self-interference (the transmitted signal) is known at the receiver and we do not need to decode it, as in [12]. Secondly, the self-interference signal is strong due to the proximity of the transmit and the receive antennas. Such a strong signal will typically saturate the digital-to-analogue conversion circuit and no further digital processing will be possible. Therefore, in our setting the transmitted signal has to be cancelled in the analogue domain.

We built a prototype of a wireless device with the analogue interference cancellation based on Quellan QHx220 noise cancellers. We feed the signal from the transmit antenna (the self-interference) through a wire to the QHx220. We also connect QHx220 to the receive antenna. The Quellan noise canceller subtracts the self-interfering signal from the received signal and recovers the useful signal.

The signal received from the wire is a good replica of the self-interfering signal received through the air, via the receive antenna. Both signals will be exposed to the same transfer functions of all circuitry. The only difference between the signals is caused by signal propagation through the air. The Quellan noise canceller contains an analogue circuit that tracks and emulates the propagation channel using an analogue filter. The design of the noise canceller is described in [13].

This approach is simple and cheap, since it requires

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[2] We have not yet implemented a full OFDM receiver for white space but we interpolate the corresponding rates from the measurements in [8].

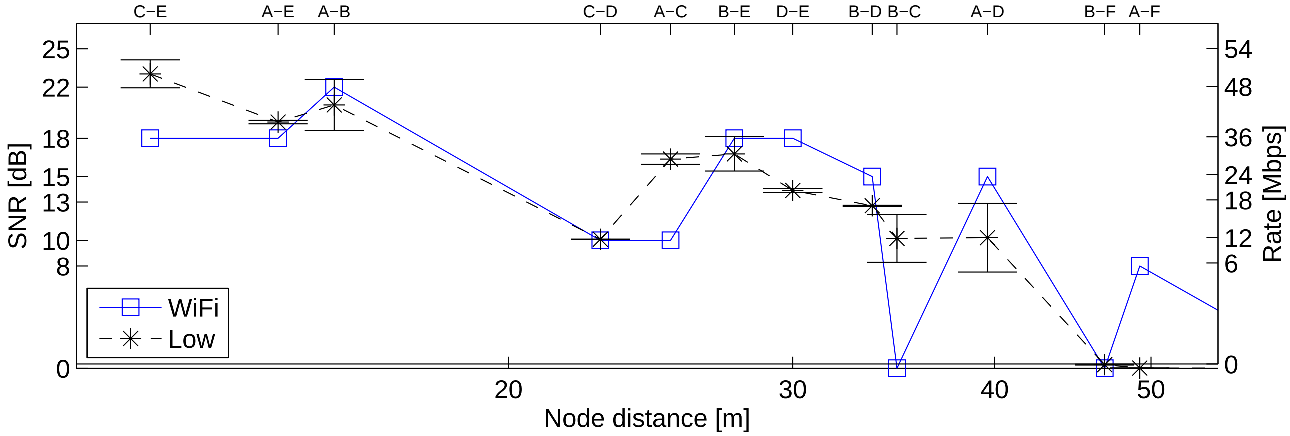

Figure 2: The average SNR and the corresponding rates for different links in the network from Figure 1. On the top x axis we mark each link and on the bottom x-axis we plot the corresponding link lengths. On the left y-axis we plot the average SNR and on the right y-axis we plot the corresponding transmission rate, based on the measurements from [8].

only a single additional analogue circuit with no modification of the physical layer. It works with any modulation scheme (OFDM, CDMA, etc.).

To assess the performance of self-interference cancellation, we use the configurable radio hardware described in Section 3.1. We attached the Quellan noise canceller at the outputs of the SDR and tuned the parameters to achieve the optimal cancellation.

We first measured the self-interference without the noise canceller circuit. The power of self-interference at the receive antenna was 55 dB (relative to the power of the background noise). We then measured the power of the self-interference after cancellation. It was about 25 dB. In other words, we successfully cancelled 30 dB of interference, confirming the results of [13] in our setting.

4.2 Nulling Antenna

The power of the self-interference over white noise is 55 dB, and we were able to cancel 30 dB using analogue interference cancellation. To completely eliminate the self-interference, we need to cancel an additional 25 dB of interference.

We are currently investigating the use of a nulling transmit antenna to achieve the additional cancellation. One of the most promising approaches is the printed annular slot antenna presented in [14]. This is an implementation of a nulling antenna that gives an almost omnidirectional radiation pattern, except in the nulling direction. The angular width of the nulling direction is approximately $10^\circ - 15^\circ$.

The nulling direction can be controlled, and we can position this direction to match the position of the receive antenna. The antenna is able to cancel between 25 dB – 30 dB of interference in the nulling direction. It is also relatively compact in size, simple, and cheap to produce.

The only potential problem with the antenna is the quality (the received SNR) of links in the nulling direction, which will be 25 dB lower. As the nulling direction is narrow, we hope to be able to receive some of the reflected paths. This remains to be evaluated in practice.

4.3 Performance of Full-Duplex

We next discuss the performance of full duplex. A major concern is that having introduced the residual noise from the self-interference, we degrade the link performance. In particular, the longer the link, the greater the sensitivity to the self interference. How much interference do we need to cancel to make full-duplex communication useful and at what range?

To answer to this question, consider a simple scenario with a single link A-B of length l where both nodes A and B have packets to send to each other. Let P be the transmit power and N the white noise power. Consider first the half-duplex case. Suppose that the link is symmetric and denote the signal-to-noise ratio at nodes A and B by $\mathrm{SNR}_A = \mathrm{SNR}_B = P\,bl^{-\alpha}/N$, where b and α describe the signal propagation as given in (1). By symmetry, the half-duplex rates $r_{HD} = r_{AB} = r_{BA}$ on the two links are equal. Using Shannon's formula (rate $= \frac{1}{2}\log(1 + \mathrm{SNR})$) gives the achieved rates as

$$r_{HD} = \frac{1}{4}\log\left(1 + \frac{P\,bl^{-\alpha}}{N}\right) \approx \frac{1}{4}\log\left(\frac{P\,bl^{-\alpha}}{N}\right),$$

since typically $P\,bl^{-\alpha}/N \gg 1$. The extra factor of $1/2$ is a consequence of the two links, A-B and B-A, needing to time-share the medium access since they cannot simultaneously transmit. The performance of the half-duplex is approximately the same in the 802.11a network and in the Low Frequency, Low Power network, as discussed in Section 3.

Now consider the full-duplex case. The transmit and receive antennas are at distance d (in our case $d = 10$ cm) and the self-interference is $P\,bd^{-\alpha}$. Let us denote by γ the fraction of interference we successfully cancel (e.g. $\gamma = 30$ dB with analogue interference cancellation only). The residual self-interference is then $P\,bd^{-\alpha}/\gamma$. Again, the scenario is symmetric and we have

$$r_{FD} = \frac{1}{2}\log\left(1 + \frac{P\,bl^{-\alpha}}{P\,bd^{-\alpha}/\gamma + N}\right) \approx \frac{1}{2}\log\left(\frac{l^{-\alpha}}{d^{-\alpha}}\gamma\right),$$

when $P\,bd^{-\alpha}/\gamma \geq N$. As one can see, the performance of the full duplex depends on the propagation parameter α (and hence carrier frequency) but it is independent of the transmit power P. Since α tends to increase with frequency, the rate achieved with full-duplex typically decreases with frequency. Therefore, operating at low frequency is required to enable efficient full-duplex communication.

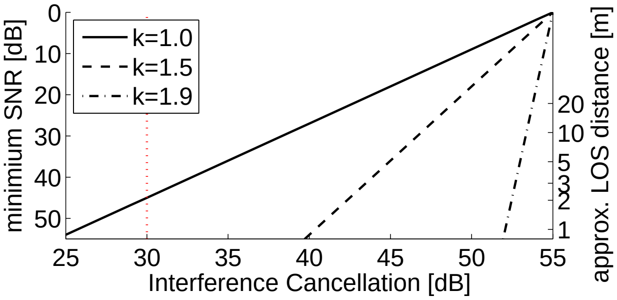

Figure 3: Minimum SNR/ maximum distance for which a given interference cancellation scheme achieves a rate improvement of factor k. On x-axis is the amount of interference cancelled (with only analogue IC we cancel 30 dB which is denoted with a dotted line; with both techniques we cancel 55 dB). On the y-axis is the minimum SNR and corresponding maximum LOS distance (derived from Figure 2) for which such a cancellation will produce k times rate improvement.

Now suppose that we require the rate achieved with full-duplex to be at least k times better than that achieved with half-duplex, that is $r_{FD} > k\,r_{HD}$, for $1 \leq k \leq 2$. k is bounded above by 2 since clearly we can at most double the rate. We then ask what is the maximal SNR, or equivalently what is the maximum link length (range) at which such an improvement can be achieved. This is illustrated in Figure 3 for the parameters of the Low power, Low frequency network described here. With analogue interference cancellation only, we cancel 30 dB of noise (shown by the vertical dotted line) and we improve performance ($k \geq 1$) for all links with the received SNR > 50 dB, corresponding to a LOS link of about 2m. But with an additional nulling antenna, described in Section 4.2, which cancels an additional 25 dB, there is no residual self interference and we always double the throughput, *regardless* of link length.

4.4 Towards Full-duplex Network Design

Finally, we list some interesting issues and challenges in the network design for full-duplex. Given the interference cancellation and nulling techniques, a node is able to transmit and receive at the same time. A node A receiving data from a node B can transmit data back to B (conventional full-duplex). But it could also transmit to some other node C, provided that A and C do not interfere. Thus, node A has the freedom to adapt its schedule to the traffic pattern. In particular, if A is an access point, it will frequently have packets to send and receive from several nodes in the network. This means that we don't need symmetric traffic in a network to fully exploit the capabilities of full duplex.

Full-duplex transmissions also eliminate the remaining hidden terminal problems. If a node A is transmitting while receiving, it generates a signal around it, preventing nearby nodes to start transmitting and hence interfere with the reception at A. This way we "fix" the carrier sensing by making it symmetric. We don't need RTS/CTS signalling procedures that are known to be inefficient and do not always prevent hidden terminals.

An interesting question is how to design the medium access in a full-duplex network. We propose keeping carrier sensing (unlike e.g. [12]). A node, say node B, that acquires the medium initiates a transmission to node A. Then only node A is allowed to transmit at the same time. Node C, the receiver of A's transmission, is not.

5. RELATED WORK

There is a large body of work on architecture and design of white-bands networks (see [6] and references therein). However, unlike us, they focus on high power, long distance networks. Lots of papers discuss different techniques to deal with non-uniform connectivity of WiFi networks [1, 2, 10].

Our paper belongs to a group of papers that propose several concurrent transmissions by exploiting advanced signal processing in wireless network design. A form of multi-user detection is presented in [15]. An recent implementation of interference cancellation is given in [12]. Our paper uses similar techniques but in a full-duplex setting and with a different MAC design. Other similar techniques include [16], which is orthogonal to our approach.

Several ways of combating hidden terminals have been proposed: using a busy tone [17] (this requires a second signaling channel which we don't need here), floor acquisition [18], signal processing [19], directional antennas [20]. We use antenna design to fight hidden terminals in a very different way than [20].

MIMO is another way to use multiple antennas. In theory, our approach could be combined with MIMO.

However, this would require more sophisticated antenna design, larger complexity and it is unlikely to work in practice. The expected gains from using MIMO in TV bands are very small, since the carrier's wavelength is large and there is much less diversity in the system.

6. CONCLUSIONS AND FUTURE WORK

We have presented a novel design paradigm for indoor wireless networks which claims that the indoor wireless should use Low carrier frequency, Low transmit power and full-duplex in a single band. We evaluated several performance aspects of such a network and we demonstrated that it can both match the connectivity of an equivalent WiFi network and give superior performance.

We propose two techniques that enables full duplex communication. We have fully implemented and evaluated the analog interference cancellation. Nulling antennas are needed to fully realize the gains of full duplex and potentially double the throughput; this is a promising research area and early indications are that the design of such antennas is possible.

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