Turning Waste into Wealth:Enabling Communication in Guardband Whitespace

Jiansong Zhang*, Jin Zhang‡, Kun Tan*, Lin Yang†, Qian Zhang†, and Yongguang Zhang*
Microsoft Research Asia*
CSE, Hong Kong University of Science and Technology†
South University of Science and Technology of China‡
{jiazhang, kuntan, ygz}@microsoft.com* {lyangab, qianzh}@cse.ust.hk† zhang.j4@sustc.edu.cn‡

Abstract

Similar to TV bands, the guardband frequencies are not occupied therefore are whitespace that potentially allows additional communication activities. Considering the difference to TV whitespace, we propose independent communication for guardband whitespace. In this paper, we present the Pilotfish system which realizes independent communication and turns guardband whitespace into new communication channels. To address the big challenges of interference mitigation, we employ novel PHY design which includes specially customized FBMC and an Nulled Decoding technique to null the strong background signal in guardbands. We implemented Pilotfish using software radio system. Empirical evaluation results validate the Pilotfish design in both PHY and MAC.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: ; C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

System, Design, Experimentation, Measurement

Keywords

Wireless; Guardband Whitespace; Independent Communication; Filtering; Nulled Decoding

1. INTRODUCTION

Spectrum resource for wireless communication has become scarce. Existing communication bands are being overwhelmed with the rapid growth of broadband access needs, which therefore has driven governments to seek for innovative use of spectrum and turn more spectrum from other purposes to wireless communications [2].

However, despite this spectrum scarcity, there is a counterintuitive fact in today's communication systems that some of the available spetrum is NOT utilized to transmit bits – a substantial part of the communication spectrum, called *guardbands*, is left unused. As shown in Figure 1, guardbands reside in two sides of every communication channel and occupy roughly 10% of spectrum in major communication systems like LTE [20] and Wi-Fi [5]. Taking Wi-Fi with 20MHz channels as an example, guardbands cause 2.2MHz-wide wasted spectrum between every two adjacent channels.

Actually, the design of guardband is not purely a waste of resource. The purpose is to insulate transmissions on adjacent frequencies to prevent mutual interference. For example, in LTE and Wi-Fi, the transmitted OFDM signal spreads quite a lot of energy into nearby frequencies, thus requires a large size of guardbands to mitigate its effect. Although guardbands could be reduced or even eliminated in theory, *i.e.* if communication systems running in adjacent frequencies can be tightly coordinated [8,22] or even OFDMA can be applied [18], in practice, fine-grained coordination between these separated systems requires complicated mechanism which is hardly fulfilled in general[1] .

In this paper, we borrow a definition which treats guardbands as a special type of whitespace [4] and address the following question: *Is it possible to utilize the "wasted" guardband frequencies for communications?* Similar to the efforts spent on TV whitespace [12], we aim for utilizing guardbands to create new communication channels that can provide meaningful capacity but do not add burden to the incumbents (*i.e.*, existing systems which occupy the communication spectrum). We expect these new channels will bring significant value, because communication spectrum is quite expensive today. For example, according to US Federal Communications Commission, the average price calculated from recent spectrum auctions is $1.5 per MHz-pop [1], meaning every megahertz has costed service providers $0.5 billion just for license [2].

The problem of designing communication system in guardband whitespace is fundamentally different from in TV whitespace. In TV whitespace, TV stations transmit in a sparse and predictable manner [12], therefore the "transmitting if idle" strategy is suitable and possible to realize with the help of TV-station database or channel sensing [12]. But in guardband whitespace, incumbents transmit in an either persistent (*e.g.*, LTE) or highly dynamic (*e.g.*, Wi-Fi) manner therefore makes database or sensing useless. In this paper, we propose *independent communication* for guardband whitespace, means communications could be conducted anytime no matter incumbents are active or not, anywhere no matter incumbents are close or far away.

Independent communication represents an ambitious design goal. It is possible to achieve because the frequencies of guardbands are not directly occupied. However, designing a system to realize independent communication is non-trivial because we need to address

MobiHoc'15, June 22–25, 2015, Hangzhou, China.

http://dx.doi.org/10.1145/2746285.2746299.

[1]OFDMA can be realized in limited cases, *e.g.* downlink of LTE inside a cell [20]. However, LTE still relies on guardbands to insulate adjacent cells that are on adjacent frequenies.

[2]given the over 300 million population in US today

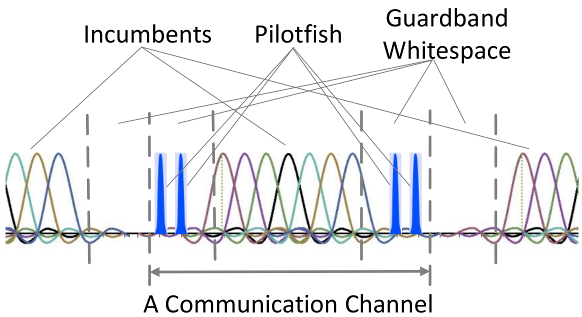

Figure 1: Pilotfish in guardband whitespace. Pilotfish works with all OFDM based incumbents and enables independent communication in the wasted guardband frequencies.

two important concerns: First, since guardband is very close to incumbent's frequency, the guardband system should suppress its out-of-band emission extremely well, otherwise it could destructively affect incumbents. The requirement on sidelobe suppression is at least -60dB, which is much higher than any existing communication system. Second, OFDM based incumbents generate strong out-of-band emission which severely pollutes the guardbands. For example, our measurements of the signal-to-interference-and-noise ratio (SINR) in guardbands was usually less than 0dB and as low as -30dB, meaning close to zero capacity conventionally.

Our solutions for these challenges are two-fold. First, we choose *Filter Bank Multi-Carrier* (FBMC) [13] as our physical layer (PHY) structure, which has been proved much more efficient in suppressing out-of-band emission than both single carrier PHY (*e.g.* DSSS) and OFDM. Second, we develop the *Nulled Decoding* technique which nulls incumbents' OFDM signal while decoding the guardband transmission, thereby significantly improving the SINR in guardbands and making decoding possible.

In this paper, we present the Pilotfish system which employs these techniques to realize independent communication. As shown in Figure 1, Pilotfish works with all OFDM based incumbents – Pilotfish devices communicate using the guardband frequencies on two sides of an incumbent band. Pilotfish achieves a spectrum efficiency comparable to or better than typical narrow-band communication systems, such as Zigbee, Z-Wave, BLE, *etc.*. Still using Wi-Fi with 20MHz channels as an example, Pilotfish creates 1.22Mbps independent communication channels using the 2.2MHz guardband frequencies. Moreover, Pilotfish brings the benefit of new communication channels without causing interference to incumbents or requiring modification to incumbents. Benefitting from its advanced PHY techniques, Pilotfish also does not require synchronization between Pilotfish transmitters and incumbent transmitters or being sensitive to the frequency offset between the transmitters.

We have built a prototype of Pilotfish using the Sora software radio system [19]. As transmitting in LTE bands requires license, we only built the prototype for Wi-Fi in unlicensed band, though the Pilotfish design can be applied to both. We evaluated both PHY and MAC based on the prototype. Experimental results validated the Pilotfish design. Specifically, 1) we prove that Pilotfish transmissions do not interfere with incumbent transmissions. 2) We show Nulled Decoding is able to greatly improve SINR in guardband and therefore enable the decoding in guardband whitespace. The SINR improvement is not affected by clock phase noise, frequency offset or multipath channel. 3) We prove the Pilotfish MAC is effective.

To demonstrate the benefits that Pilotfish brings, we also propose two applications of Pilotfish.

In summary, we make the following contributions: 1) We propose independent communication in guardband whitespace, which creates new communication channels without requiring spectrum resource. 2) We propose the Pilotfish system which employs advanced PHY techniques to address the uncommon challenges in guardband whitespace. 3) We implemented Pilotfish using software radio and verified the Pilotfish design through experiments.

2. Pilotfish OVERVIEW

This section provides an overview of Pilotfish. First we discuss the widely adopted guardband design as the background of this paper. Then we describe our *independent communication* strategy for transmissions in guardband as well as the challenges to realize this strategy. Finally we briefly introduce filter bank multicarrier to explain why we choose it for Pilotfish's PHY structure.

2.1 Guardband in Communication Systems

Guardband is a widely adopted design in wireless systems. The purpose is to protect the systems that are in adjacent frequency bands by insulating them from mutual interference, where the systems could be designed for either the same or different purposes (*e.g.*, communication *vs.* radar or TV broadcast), or used in either the same or different manners (*e.g.* exclusive in licensed bands *vs.* shared in unlicensed bands). The guardband design is also commonly used for systems inside a frequency band, for example, to insulate adjacent Wi-Fi channels in 5GHz ISM band [5] or insulate adjacent LTE channels in LTE band number 41 [20].

The guardband design leaves a substantial portion of the precious spectrum resource unused. For example, according to the IEEE 802.11 standards [5], 2.2 $\sim$3.4 MHz of a Wi-Fi channel is left as guardband, which results in more than 10% waste for 20 MHz channels. The number in LTE is similar [20]. The size of guardband highly depends on frequency domain characteristics of the transmitted signal. Majority of the advanced communication systems, including Wi-Fi and LTE, employ OFDM as their PHY design for high spectrum efficiency and low complexity [15]. The problem of OFDM is that it spouts quite a lot of energy into adjacent channels, therefore requires a large guardband size.

2.2 Independent Communication in Guardband Whitespace

Similar to the TV whitespace, we can potentially conduct communication using the unused frequencies in guardbands. In this paper, we adopt an existing definition [4] to term it *guardband whitespace*. The goal of this paper is to develop techniques to conduct communication effectively and efficiently in guardband whitespace.

Similar to the communication in TV whitespace, communication in guardband whitespace should also avoid generating interference to incumbents and prevent themselves from being interfered by incumbents. However, the strategies for communication are totally different because the behaviors of incumbents are different. In TV whitespace, the communication systems try to utilize the frequencies which were allocated for TV broadcasting because some frequencies are rarely used in some regions. Usually, the schedule of TV broadcasting is available in advance and the location of TV stations is fixed. Therefore, the strategy of "transmitting if idle" is necessary to prevent incumbents and sufficient to prevent themselves. However, in guardband whitespace, the same strategy will be neither necessary nor sufficient. Since guardband is not directly occupied, it is possible that the communication does not generate noticeable interference to the incumbents (*i.e.* existing wireless systems). Since the incumbents could have unpredictable behavior, it will be very difficult to determine an idle time. For example, in

LTE bands, the incumbents (base stations) transmit persistently, in Wi-Fi bands, the incumbents (APs and stations) transmit in a highly dynamic manner (on per-packet basis).

In this paper, we propose *Independent Communication* as our strategy for guardband whitespace, which means communication does not depends on the status of incumbents, *i.e.* no matter they are active or silent, no matter they are close or far away. Independent communication represents an ambitious design goal that if achieved, the communication system will be possible to be inserted in any existing wireless systems' guardband. With independent communication, we remove the burden of additional database or channel sensing as in TV whitespace, but need to rely on advanced PHY techniques to protect both the guardband communication system and incumbents. The requirement for PHY design is actually very high because we need to address two uncommon challenges in communication system design as follows.

First, the guardband system should suppress its out-of-band emission extremely well. Different from exisiting narrow band systems (*e.g.* Zigbee, Z-wave and bluetooth) in which both a system itself and its adjacent system are based on spread spectrum PHY (*e.g.* DSSS)[3], the guardband system in our design must handle adjacent systems based on OFDM. Spread spectrum systems have a nice property that OFDM systems do not have, *i.e.* resistant to cross-interference because of the employed spreading code (*e.g.* CDMA) [16]. Therefore the requirement on out-of-band suppression is reduced. However, to protect OFDM based incumbents, we must suppress guardband system's out-of-band emission much better. We set our goal as a emitted energy level comparable to noise floor, meaning $60dB$ to $80dB$ sidelobe suppression.

Second, since the guardband system is designed to work concurrently and independently with incumbents, the guardband system must handle potentially very strong background signal emitted by incumbents. As characterized with transmit power mask [5, 20], OFDM based incumbents emit a energy level merely $20dB$ less in guardband than in their center frequency. To obtain a rough understanding of the SINR in guardband, we set up a 9-node test-bed with commodity Wi-Fi cards, in which every node can hear from all the other nodes. We recorded received signal strength indicator (RSSI) on every link, then calculated SINR in guardband using a model with three nodes: one node as guardband transmitter, one as guardband receiver and one as incumbent transmitter. In this caclulation, we assumed the same transmit power density of guardband transmitter as incumbent transmitter, and derived the RSSI in guardband from transmit power mask. Results are shown in Figure 2. We exclude the cases that guardband transmitter is stronger than incumbent transmitter because they are trivial to handle. We can see in many cases, the SINR in guardband was less than $0dB$. In some cases, the SINR was even as low as $-30dB$. Conventionally, this SINR level means impossible for meaningful transmission, or as low as 1 bit per Wi-Fi packet with 20MHz channel [17].

2.3 Filter Bank Multi-Carrier

In this paper, we propose the Pilotfish system to realize independent communication in guardband whitespace. To address the uncommon challenges mentioned in above subsection, we propose a novel PHY design in Pilotfish. As the basis, we choose *Filter Bank Multi-Carrier* (FBMC) [13] as Pilotfish's PHY structure. In this subsection, we briefly introduce the advantages of FBMC to facilite the detailed discuss of Pilotfish's PHY in next section.

FBMC, as the same as OFDM, is a form of multi-carrier modulation that contains a set of narrow subcarriers. It therefore enjoys the advantages of multi-carrier modulation, *e.g.* high spectrum efficiency, immunity to multi-path fading and impulse noise, enhanced immunity to inter-symbol interference, *etc.* [16]. However, different from OFDM which causes strong out-of-band emission because of the employed time-domain window function as subcarrier filter, FBMC can suppress out-of-band emission arbitrarily well because of its flexible choice of subcarrier filter. Therefore, FBMC is a good choice for Pilotfish. FBMC also has another advantage that it does not require symbol synchronization as OFDM, because it can insulate subcarriers with properly designed subcarrier filter. Therefore FBMC based scheme could be a better choice for multiple access than OFDM based scheme (*i.e.* OFDMA) when symbol synchronization among multiple transmitters is difficult.

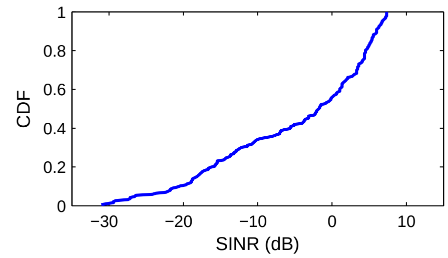

Figure 2: Measured guardband SINR from a 9-node test-bed.

3. PILOTFISH DESIGN

This paper presents Pilotfish[4], a system that realizes independent communication in guardband whitespace. Pilotfish represents a novel communication system design which addresses the uncommon challenges mentioned in above section using advanced PHY techniques. Specifically, Pilotfish employs FBMC as its PHY structure for the purpose of better suppressing its out-of-band emission. In §3.1 we will discuss the filter design in details as well as its impact. We also develop the *Nulled Decoding* technique to enable decoding under the extremely low SINR in guardband. Nulled Decoding leverages the orthogonality property of OFDM to null the emitted signal from incumbents. In §3.2 we will elaborate Nulled Decoding. Finally, in §3.3 we will discuss additional design considerations for truely independent guardband transmission with incumbent transmission.

For the sake of simplicity, we choose CSMA as Pilotfish's MAC. We leave other choices, *e.g.* frequency domain multiple access, as our future work which may be a better choice in centrally controlled wireless systems such as cellular networks.

3.1 Filter Design

The first requirement of Pilotfish is extremely well out-of-band emission suppression. This is achieved by applying a carefully designed filter in Pilotfish's FBMC PHY. In the following, we will first discuss the requirement of such a filter, and then we describe how we can design a digital filter that satisfies the requirement.

Figure 3 shows a simple prototype filter that divides the response of the filter into three parts: a pass-band, a stop-band, and a transition-band [6]. The stop-band rejection is defined as the ratio of the signal strength at the stop-band to that in the pass-band (in dB), *i.e.*, how much signal has been suppressed by the filter. The goal of our filter design is that the signal leakage at the stop-band would be as low as noise floor (*i.e.*, -90dBm), and thus the interference to nearby data communication can be neglected. Assuming the transmission

[3]These systems only consider intra-protocol interference in their design. Cross-protocol interference is still an research problem.

[4]We name the system after a cute family of fish that usually lives around big sharks or sea turtles, which is a metaphor for guardband communication system that works concurrently with incumbents.

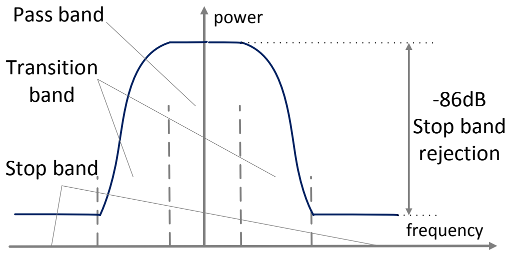

Figure 3: Prototype filter used in Pilotfish.

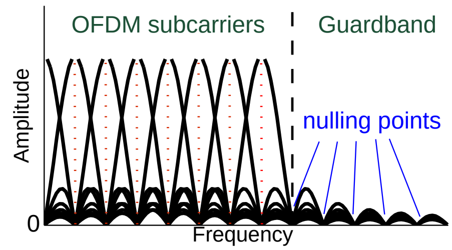

Figure 4: Multiple nulling points in guardband.

power at the guardband channel is the same as Wi-Fi, *i.e.*, 20dBm, a receiver that is 1 foot apart would sense the signal strength as -30dBm – the path loss is about 50dB [17]. Therefore, in order to suppress the signal at the stop-band to noise floor, the stop band rejection should be at least -60dB.

Such a high rejection is very difficult to be implemented with conventional *finite impulse response* (FIR) filter as it may require a very long taps that incurs prohibitive computation overhead. To overcome this issue, in Pilotfish, we choose to use an *infinite impulse response* (IIR) filter. Specifically, we choose Type I Chebyshev filter [11] as the ripples in stop-band is very small. The implementation of such a filter is actually simple. It requires only 20 additions and 26 multiplications per symbol, which is comparable to a 26 taps FIR, therefore can be easily handled by modern digital signal processing (DSP) units. The stop-band rejection of our filter is actually -86dB and the transition-to-pass band ratio is 2.

The downside of such an IIR filter, however, is that the signal will spread out in the time domain. Therefore, it is not an ISI-free filter. ISI is generally considered harmful in communication as this self-interference caps the SINR of the channel, no matter how high the transmission power is. However, this SINR bound, 12 dB in our design, is not truely a critical issue for Pilotfish, because the SINR in guardband is far lower in many cases as shown in §2.2. Moreover, the application based on Pilotfish (§6) may only require broadcasting which is transmitted in low modulation rate anyway for reliability.

3.2 Nulled Decoding

While the filter prevents guardband transmission from interfering with incumbents, the incumbents, however, still spill significantly amount of energy into guardband (§2.2). Fortunately, the incumbents are mostly based on OFDM, which has a unique signal structure that we can explore to remove the interference.

Figure 4 illustrates the signal structure of an OFDM symbol. OFDM divides a channel into many small and partially overlapping subcarriers. The central frequencies of these subcarriers are carefully chosen so that they are "orthogonal" to one another, meaning that cross-talk of all other subcarriers sums up to zero at the central frequency of any subcarrier. Similarly, we can also find such points in guardbands where interference from all data subcarriers also sums to zero. These points are called *nulling points*. If we can just "take samples" of the guardband transmission at these nulling points, the data transmissions actually do not interfere with the guardband communication – as all interference is nulled at this "sampling point" (in frequency domain). Therefore, we call this technique as *Nulled Decoding*. Taking samples in frequency domain is realized using FFT, which is a basic building block of both OFDM receivers and Nulled Decoding based receivers. At the end of this section, we provide simple mathematics to describe the orthogonality of OFDM and Nulled Decoding in more detail.

To find these nulling points in guardbands is actually simple. Imaging that if we fill the guardband with additional OFDM subcarriers, then the central frequencies of the added subcarriers are the nulling points in guardbands. For example, in Wi-Fi with 20MHz channel and HT mode, as defined in the standard [5], subcarrier -32∼-29 and 29∼31 are located in guardbands, and their central frequencies form the nulling points. Since Nulled Decoding takes samples from nulling points, Pilotfish aligns the subchannels of its FBMC PHY[5] with these nulling points. Specifically, around each nulling point, we place a Pilotfish subchannel, which has a width roughly the half of an incumbent OFDM subcarrier (125 KHz wide for Wi-Fi). To provide further isolation from incumbents, Pilotfish explicitly leaves the two nulling points adjacent to incumbent unused. Therefore, using Wi-Fi with 20MHz channel as an example, we can have 9 (non-HT mode) or 5 (HT mode) Pilotfish subchannels, respectively.

Same as OFDM subcarriers, the frequency separation between two Pilotfish subchannels is 312.5 KHz. According to the filter design in §3.1, one subchannel lies in the stop-band of the other. Therefore, the interference between subchannels is minor. In other words, Pilotfish satisfies the requirement of a FBMC PHY with its filter design and its subchannel separation.

The Pilotfish receiver then "takes samples" for the subchannels at these nulling points. It is achieved by simply performing FFT on the received signal, and the FFT outputs with the corresponding indexes are picked up. In this case, FFT can be regarded as a matched filter at the receiver side, and only samples on these nulling frequencies are retained. To enable this simple sampling, the major requirement for Pilotfish receiver is to determine symbol boundaries according to the symbols of incumbent's transmission.

To summarize the PHY design of Pilotfish, we first carefully choose parameters of the filter and locations of the subchannels to construct the FBMC PHY, then we use OFDM-like receiver to decode the FBMC transmissions. Pilotfish represents an uncommon *hybrid* PHY design, which therefore can solve the two uncommon challenges for communication in guardband whitespace. In the following, we discuss two practical issues of the Pilotfish PHY.

One issue is frequency offset. As shown in Figure 5, since there may be certain frequency offset between Pilotfish transmitter and incumbent transmitter, the Pilotfish receiver will not be able to *synchronize* its frequency[6] to both of them. In our design, we choose to synchronize to incumbent transmitter, *i.e.* to "take samples" from the nulling point instead of central frequency of the subchannel. The purpose is to optimize the performance of interference nulling. In this case, Pilotfish receiver must handle a slight non-compensatable frequency offset to Pilotfish transmitter. Therefore,

[5]Although subchannel and subcarrier could be used interchangeably, in this paper we only use "OFDM subcarrier" and "Pilotfish/FBMC subchannel" to differentiate two PHY structures.

[6]usually through frequency compensation algorithms

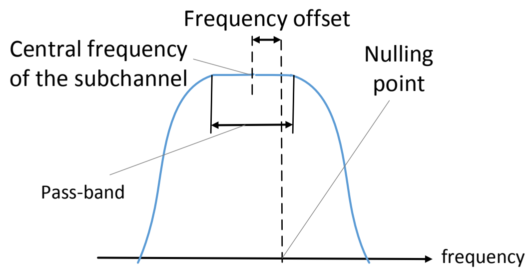

Figure 5: Frequency offset between Pilotfish transmitter and incumbent transmitter causes mis-alignment between Pilotfish subchannel and the nulling point. We choose to "take samples" from the nulling point to optimize nulling performance. SNR loss due to this mis-alignment will be small as long as the frequency offset is within pass-band of the Pilotfish filter.

we always use differential modulation for Pilotfish to address this frequency offset, as the same consideration in some DSSS PHYs. We notice that this slight frequency offset still causes loss in signal strength because the samples are not taken from central frequency of a subchannel. However, since the filter has a flat shape near its center, this SNR loss will be small as long as the frequency offset is within pass-band of the filter (125/2 KHz in case of Wi-Fi).

The other issue is the emitted energy from the incumbent in adjacent channel. It cannot be nulled because Pilotfish receiver is not able to align symbol boundary simultaneously to multiple unaligned incumbents in adjacent channels. We handle this issue with following three approaches: 1) As shown in Figure 1, the spectrum hole between two adjacent incumbents are divided into two equal parts that each part is associated with the closer incumbent. In this way, we still reserve a half-sized guardband between Pilotfish and the adjacent incumbent. 2) Considering the same power limit of devices, Pilotfish can use high power density than incumbents because of the narrower bandwidth, therefore provides additional gain. 3) We use a strong channel code to protect Pilotfish transmissions. As we will show later (§5), Pilotfish is more reliable than incumbents to the same interference from adjacent channel.

The Orthogonality of OFDM and Nulled Decoding. We provide simple mathematics as follows. Basically, the time-domain waveform $Y = [y_1, y_2, \cdots, y_N]^T$ of an OFDM symbol is generated using the linear equation:

$$Y = W \cdot X \tag{1}$$

where the vector $X = [x_1, x_2, \cdots, x_N]^T$ is the frequency-domain representation of the symbol which is generated by mapping information bits into signals using constellation maps, and the matrix $W = [w_1^T, w_2^T, \cdots, w_N^T]^T$ is the inverse Discrete Fourier Transform (IDFT) matrix which consists of a set of DFT vectors. DFT vectors have the property that they are orthogonal to each other, *i.e.*

$$w_p \cdot w_q^* = \begin{cases} 1, if p = q \\ 0, if p \neq q \end{cases} \tag{2}$$

where w_q^* is the conjugate transpose of w_q. Benefiting from this orthogonality property, we can easily recover each signal x_k from Y that we multiplying Y by the conjugate transpose of the corresponding DFT vector w_k, *i.e.*

$$w_k^* \cdot Y = w_k^* \cdot [w_1^T, w_2^T, \cdots, w_N^T]^T \cdot X = x_k, \tag{3}$$

In practice, Equation (1) is realized using IFFT (Inverse Fast Fourier Transform) and Equation (3) is realized using FFT (Fast Fourier Transform).

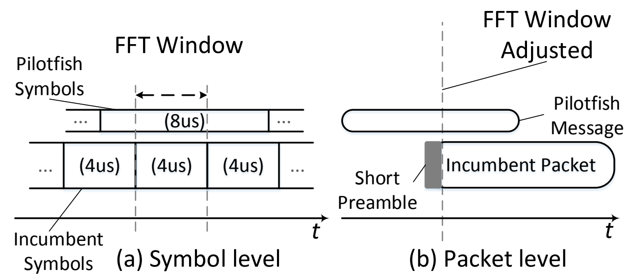

Figure 6: (a) Larger (2x) Pilotfish symbol size enables truely independent transmissions. (b) FFT window is adjusted upon a new short preamble.

The idea of the Nulled Decoding technique is to leverage the fact that some elements of the frequency-domain symbol X are left as zero for the purpose of constructing the guardbands. Therefore, at the receiving side, if we pick the FFT outputs (*i.e.* take samples) corresponding to these elements, the received OFDM symbol will be entirely nulled.

3.3 Independent Pilotfish Transmissions

As mentioned above, the Nulled Decoding technique requires Pilotfish receiver to perform FFT within the same FFT windows of an OFDM symbol in incumbent transmissions. Otherwise, the orthogonality property will be lost and interference will increase. However, if Pilotfish transmission is independent to incumbent transmission, their symbol boundaries will not be aligned.

Instead of explicitly aligning Pilotfish symbols to incumbent symbols, we prefer truely independent transmissions. Therefore, in our design we set Pilotfish's symbol size to be twice of the incumbent symbol, as shown in Figure 6(a). In this way, we ensure that we can always find a good FFT window from every two incumbent symbols that is perfect for both nulling and sampling. Considering Wi-Fi that an OFDM symbol is $4\mu s$, the symbol size of Pilotfish will be 8 μs accordingly. We further notice that twice the symbol size also means half the Pilotfish subchannel width of incumbent subcarrier, as mentioned above.

Considering asynchronous incumbent transmissions such as Wi-Fi, the FFT window should be adjusted for every incumbent packet, because successive packets are unaligned in symbol boundaries. In our design, this FFT window adjustment is performed right after the symbol boundary determination from a newly received short preamble (*i.e.* Short Training Sequence or STS), as shown in Figure 6(b).

Summary. We have described the techniques we used in Pilotfish to enable independent communication in guardband whitespace without introducing additional interference to incumbents. The Pilotfish PHY is based on FBMC which comprises a group of subchannels, each of which is aligned to a nulling point in guardband. We employ a digital Chebyshev filter to suppress the out-of-band energy emissions to be as low as $-86dB$. The Pilotfish receiver uses Nulled Decoding to null out the interference from incumbents and therefore obtains a reasonably high SINR to support communication. We estimate the overall capacity of the Pilotfish design for Wi-Fi guardbands as follows. As mentioned earlier, the SINR in a Pilotfish subchannel is capped at 12 dB due to ISI. This is enough to support 16QAM 1/2 coded frames. Taken the symbol rate 125 KHz, the overall capacity of one subchannel is

$$C_{sc} = 125K * 4bit/2 = 250Kbps.$$

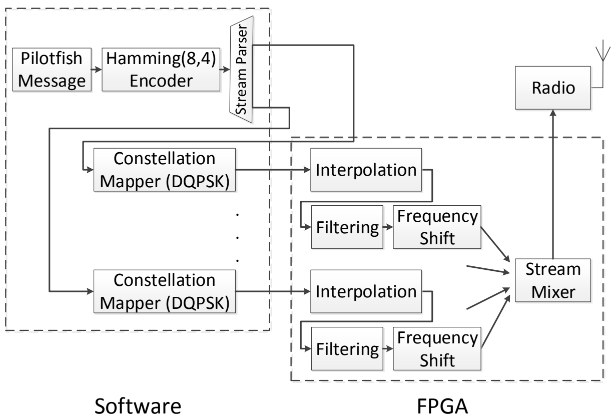

Figure 7: Pilotfish transmitter. It contains multiple streams for multiple subchannels. Multiple instances of the filter are implemented in FPGA to accelerate the computation.

So, in case of Wi-Fi HT mode with 20MHz, we can have up to 5 such subchannels. Therefore, the aggregate capacity of Pilotfish is 1.22M bps. In general, this gives a meaningful capacity that is comparable to existing narrow band systems (Zigbee, *etc.*).

3.4 Discussion

We now briefly touch upon some practical issues in the design.

Mobility. Device mobility brings Doppler effect and additional frequency offset, thereby introducing an additional challenge. According to our experience, device mobility associated with human movement can be easily handled by modern OFDM based wireless systems. This level of mobility also does not add problem to Pilotfish as Pilotfish shares the same principle with OFDM systems.

Requirements on the Pilotfish receiver. The Pilotfish receiver should be able to entirely receive incumbent's signal, estimate and compensate frequency offset, and calculate DFT outputs on the nulling points. Since these requirements are already fulfilled by the incumbent receiver, we can leverage the incumbent receiver to simplify the implementation of Pilotfish (such as our implementation) if the device is designed to have both functions. However, the Pilotfish receiver also can be implemented independently.

Varying channel width and overlapping channels. In some cases, the guardband may be overlapped with some other incumbent systems. For example, in 5GHz band, the Wi-Fi channel-width is varying, in 2.4GHz band, not only the channel width is varying, but also the channels are overlapping. In these cases, the Pilotfish transmitter relies on carrier-sensing to avoid conflicting with incumbents.

4. IMPLEMENTATION

As transmitting in LTE's bands requires license, we built the Pilotfish prototype only for Wi-Fi which uses unlicensed bands. We implemented the prototype using Sora [19] software radio system. The incumbent Wi-Fi was the SoftWiFi implementation on Sora which has been proven compatible with commodity Wi-Fi card.

For the sake of simplicity, we chose Hamming(8,4) code with 1/2 coding rate, DQPSK, and four Pilotfish subchannels that every two are on a side of a Wi-Fi channel. Therefore, each byte of Pilotfish message is encoded into two symbols carried in four parallel streams (subchannels). As a result, the data rate is 500kbps.

4.1 Pilotfish Transmitter

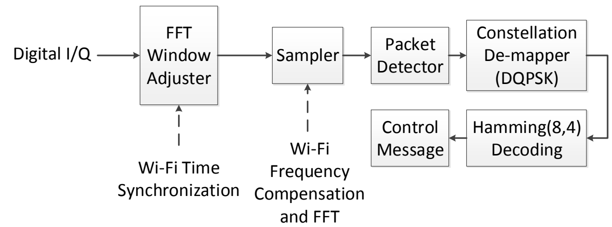

Figure 8: Pilotfish control decoder. It takes advantage of time synchronization, frequency compensation and FFT calculation of Wi-Fi decoder.

Figure 7 presents the modules of Pilotfish transmitter. As shown in the figure, a Pilotfish message is first encoded by Hamming(8,4) encoder. Then coded bits are divided into four streams by stream parser. Each bit stream is mapped to constellation points (I/Q) independently by DQPSK modulator. After that, each modulated I/Q stream is interpolated from 125KSPS to 40MSPS to match sampling rate of DAC. Digital IIR filtering is performed on 40MSPS samples for every stream, after which filtered streams are shifted to corresponding nulling points. Finally, four signal streams are mixed together to generate the final waveform.

The digital IIR filter is computationally intensive for software radio. Comparing to the 37-tap FIR shaping filter implemented in SoftWiFi 802.11b [19], Pilotfish's four steams need four filter instances which summing up requires approximately 3x computation as 802.11b's filter. In order to accelarate the computation, we implement the filters in the FPGA of Sora radio adapter board (RAB). To avoid crossing software/FPGA interface multiple times, we also implement interpolater, freuqency shifter and stream mixer in FPGA. Other modules, *e.g.* Hamming encoder, stream parser and constellation mapper, are implemented in software using Sora UMX API [3].

4.2 Pilotfish Receiver

Figure 8 presents the modules of Pilotfish receiver. For the sake of simplicity, we continuously perform FFT and take Pilotfish samples on received digital I/Q, no matter there is any Pilotfish transmission or incumbent transmission. Then, packet detection, constellation de-mapping and Hamming decoding are performed based on these samples output from FFT. We notice that this implementation is not optimal in terms of power efficiency. To improve, we could use a Zigbee-like narrow band receiver while there is no incumbent transmission. We leave this optimization for our future work. As discussed in §3.3, the FFT window should be adjusted upon a new incumbent packet. The window adjuster is triggered by SoftWiFi's time synchronization module. To save computation, we reuse the FFT calculation in Wi-Fi decoder to take Pilotfish samples. Moreover, SoftWiFi performs frequency compensation to mitigate frequency offset between Wi-Fi transmitter and Wi-Fi receiver. We also reuse this frequency compensation for Pilotfish receiver. Finally, we notice that all modules of Pilotfish receiver are implemented in software.

5. EVALUATION

In this section, we present the empirical evaluation for the Pilotfish design. We set up a small test-bed to conduct the experiments. The basic setting consists of three nodes, *i.e.* one 20MHz-wide Wi-Fi transmitter, one Pilotfish transmitter and one receiver which is capable for both Wi-Fi decoding and Pilotfish decoding. The Pilotfish transmitter and Wi-Fi transmitter always transmit simul-

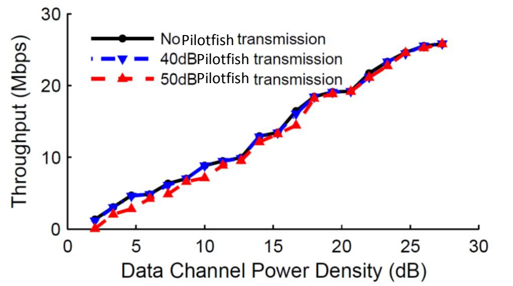

Figure 9: The Pilotfish filter suppresses its out-of-band emission very well. As a result, the strong Pilotfish transmissions with 50dB power density generate neglectable interference to incumbent Wi-Fi transmissions.

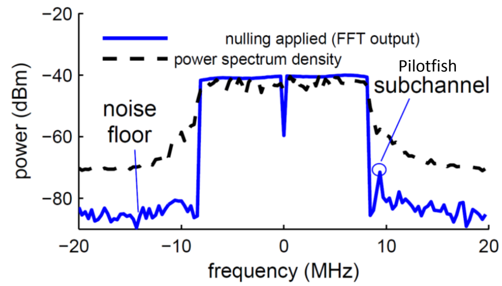

Figure 10: Nulling illustration. Two curves reflect the received signal w/ and w/o nulling. The nulling technique nulls out the emitted signal from incumbent transmissions, thereby enabling the decoding of a weak Pilotfish transmission with extremely low (-20dB) SINR.

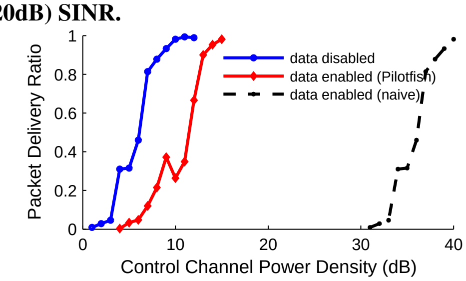

Figure 11: Pilotfish effectively nulls out 25dB of a 30dB emitted signal, remains only 5dB residual interference. This experiment uses three Sora nodes.

taneously. We adjust the power received at the receiver to assess various building blocks in Pilotfish. In general, we always evaluate the most challenging stituations. For example, we evaluate the Pilotfish filter while the transmitting power of Pilotfish is high and the power of Wi-Fi is low. Also, we evaluate Nulled Decoding while Wi-Fi power is high and Pilotfish power is low. For Pilotfish, we also evaluate the affect of clock phase noise, frequency offset, multipath channel and adjacent channel interference. In order to create the adjacent channel interference, we add a fourth node transmitting in adjacent Wi-Fi channel.

In order to fairly compare the power in Wi-Fi channel and Pilotfish channel, we should use power density (*i.e.* dBm/Hz) instead of power (*i.e.* dBm) because the channel widths are largely different. For the sake of simplicity, we use relative power density over noise instead of absolute power density. Specifically, we assume the power density of noise is identical in Wi-Fi channel and guardband. Then, we use *signal to noise ratio* (SNR) to indicate relative power density. For example, we indicate the power density of a signal as 50dB if power density of the signal is 50dB higher than noise in its occupied band. We notice that this SNR calculation is equivalent to the SNR calculated using absolute power as long as the signal is flat, which is the case in both Wi-Fi channel and Pilotfish channel.

5.1 Out-of-band Emission Suppressing

The purpose of the Pilotfish filter is to suppress out-of-band emission so that Pilotfish transmission does not generate interference to incumbent transmissions. To assess the performance in challenging cases, we set up a strong Pilotfish transmitter to check whether it interferes with Wi-Fi transmissions. To make the experiment repeatable, we use cables and power combiner to connect three nodes, then manually add attenuator or tune transmission power to adjust received power.

We tried two high values of transmitting power for Pilotfish, *i.e.* 40dB and 50dB, which means, if the 50dB Pilotfish transmissions do not interfere with Wi-Fi transmissions, the effective stop-band rejection is at least -50dB. In order to check whether Wi-Fi transmissions are interfered, we first disable Pilotfish transmitter and measure Wi-Fi throughput under different Wi-Fi channel power density (*i.e.* SNR) using broadcast packets. We also disable rate adaptation and manually find the best rate. Then, we enable Pilotfish transmitter by broadcasting back-to-back messages, and measure Wi-Fi throughput again.

In Figure 9, we plot two throughput curves together for side-by-side comparision. As shown, the 40dB Pilotfish transmissions lead to exactly the same throughput curve as Pilotfish transmissions are disabled, means no interference is introduced. The 50dB Pilotfish transmission generate slightly degraded throughput curve, means slight interference is introduced. We further check the power spectrum density of transmitted Pilotfish signal and find that the interference is not caused by out-of-band emission but induced by nolinear effect of the radio, where harmonic components of Pilotfish signal appears in the Wi-Fi frequencies. Similar obseravtion has been discussed in [7].

We notice that in real networks a 40dB power density is already extreme which means Pilotfish transmitter is very close to the Wi-Fi receiver. Therefore, we conclude that the Pilotfish filter has effectively suppressed its out-of-band emission.

5.2 Nulled Decoding

We first use Figure 10 to qualitatively illustrate how the nulling technique works. For the sake of clear demonstration, we only transmit Pilotfish signal in one subchannel. The power spectrum density of received signal shows that incumbent transmissions spill out a lot of energy to guardband. In this example, since the received Pilotfish signal is relatively weak, *i.e.* the SINR in guardband control channel is as low as -20dB, the Pilotfish signal is inundated in the emitted signal from incumbent transmissions, therefore is not detectable. When we apply Nulled Decoding by taking Pilotfish samples from the FFT output calculated on FFT windows, the emitted signal is nulled out as shown in the figure. As a result, the SINR in guardband increases dramatically.

In following of this subsections, we quantitatively evaluate the effectiveness of Nulled Decoding. In our experiments, we consider frequency offset, clock phase noise and multipath channel as the factors that potentially affect the effectiveness of Nulled Decoding. We also evaluate the robustness of Pilotfish decoding when interference from adjacent incumbent channel exists.

5.2.1 Basic Case

As a basic use case, we set up three nodes, including one Wi-Fi transmitter, one Pilotfish transmitter and one receiver capable

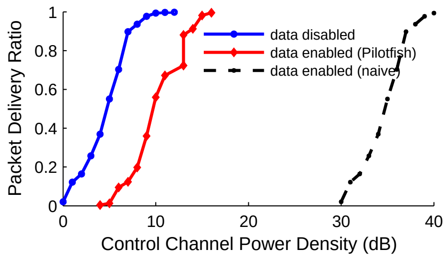

Figure 12: Eliminating frequency offset does not remove residual interference, therefore frequency offset is not the cause. This experiment uses one Sora MIMO node.

of receiving both transmissions. We focus our evaluation on the most challenging case that the Wi-Fi transmissions are very strong. Specifically, we fix the power density of Wi-Fi signal to 50dB. This strong signal generates 30dB interference in guardband. We manually add/remove attenuators to set different power density in Pilotfish channel and measure packet delivery ratio (PDR) of Pilotfish messages in various settings. To make the experiment controllable and repeatable, we use cables and power combiner to connect three radios. In subsection 5.2.4, we will present results using antennas.

We broadcast 24-bit messages in Pilotfish channel. We compare the PDR while Wi-Fi transmissions are disabled and enabled. When Wi-Fi transmissions are enabled, we broadcast 1500-byte back-to-back packets. The result is shown in Figure 11. We can see that when Wi-Fi transmissions are enabled, the PDR curve is shifted by roughly 5dB. Comparing to a naive method which treats interference as noise therefore should shift the curve by 30dB, Pilotfish equivalently nulls out 25dB interference.

Therefore, we conclude that Nulled Decoding is effective on real radio devices. However, the nulling is not perfect in the experiment that roughly 5dB residual interference still remains. In order to figure out the cause, in following subsections, we further study several potential factors.

5.2.2 *Frequency Offset*

The first factor to study is frequency offset. Every Sora device equips a cheap 20MHz *temperature compensated crystal oscillator* (TCXO) as reference clock for both carrier frequency and sampling clock. The TCXO has frequency accuracy of 10^{-6}, which causes roughly 10kHz carrier frequency offset and 100Hz sampling frequency offset between devices. We take a exclusion method for the study. Specifically, we use a Sora MIMO device to replace the three Sora devices mentioned above, by which we can emulate three devices using three radios of the Sora MIMO device. In this way, we eliminate the frequency offset between nodes because the radios share a common TCXO.

We repeat the above experiment. Result is shown in Figure 12. The result is very similar to Figure 11. Therefore, we conclude that frequency offset is not the cause of residual interference. This result is not out of expectation, because Wi-Fi decoder already contains a frequency offset compensation module. Specifically, the frequency offset is estimated from long training sequency of preamble. We find the estimation result provided by SoftWiFi is quite accurate that error is always with 1kHz. Moreover, sampling frequency offset also does not cause degradation as long as symbol boundary is correctly determined.

5.2.3 *Clock Phase Noise*

The next factor to study is clock phase noise which introduces noise to the signal. We still take the exclusion method. Specifically, we replace the TCXO on the Sora MIMO device with a much more

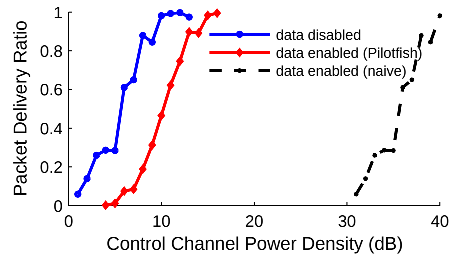

Figure 13: Replacing TCXO with OCXO does not remove residual interference, therefore clock phase noise is not the cause.

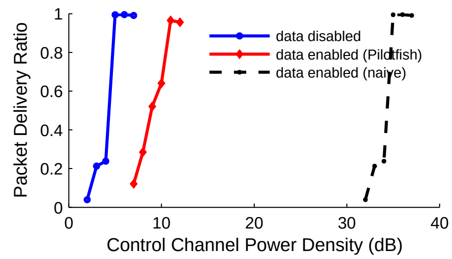

Figure 14: Multipath channel does not degrade the effectiveness of Nulled Decoding. In this experiment we use antennas instead of RF cables.

accurate *oven controlled crystal oscillator* (OCXO). The OCXO has frequency accuracy of 10^{-9} and number of magnitudes lower phase noise. We repeat the experiment again. Result is presented in Figure 13. The result is also very similar to Figure 11. Therefore, we conclude that clock phase noise is not the cause of residual interference.

Our hypothesis is that the residual interference is caused by imperfection of the RF front end. The imperfection usually contains non-linear effect that linear signal processing technique like Pilotfish is not able to handle. Solving this problem requires non-linear signal processing technique [7] or better engineered RF font end. We leave handling residual interference as our future work.

5.2.4 *Multipath Channel*

Since our experiments above are conducted using cables, a remaining concern is whether multipath wireless channel degrades the effectiveness of Nulled Decoding. To study this issue, we conduct a simple experiment by replacing cables with antennas. In order to set up a 50dB high receiving power in Wi-Fi channel, we place the antenna of Wi-Fi transmitter close to the antenna of receiver. The result is shown in Figure 14. We can see the result is similar to above. This is not out of expectation because in general OFDM handles multipath very well because of the design of cyclic prefix. Therefore, we conclude multipath channel does not degrade Nulled Decoding.

5.2.5 *Robustness under Cross-Channel Interference*

As discussed in §3.2, Pilotfish does not null out the interference from adjacent incumbent, therefore we carefully design Pilotfish's physical layer to ensure its robustness.

We conduct experiment to evaluate the robustness. Besides three Pilotfish nodes used above, we add another node to transmit in adjacent Wi-Fi channel by broadcasting 1500-byte back-to-back packets. The received power density measured in the adjacent Wi-Fi channel is 40dB. The interference in guardband and the data channel is 10∼20dB. We compare the robustness of Pilotfish transmissions to Wi-Fi transmissions in incumbent channel. For the sake of fair comparison, we present the result using bit error rate (BER)

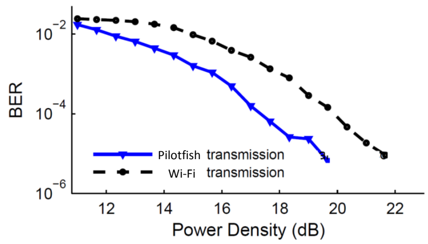

Figure 15: Pilotfish transmissions in guardband control channel are slightly more robust than Wi-Fi transmissions when cross-channel interference exists.

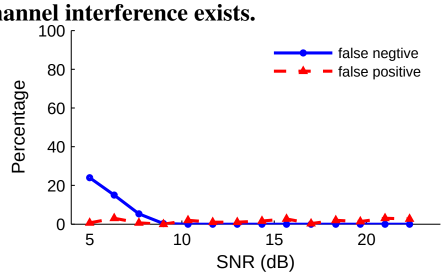

Figure 16: CCA performance of Pilotfish MAC.

instead of PDR. We also assume the Wi-Fi transmissions in incumbent channel use the lowest data rate, which is therefore the most robust. Figure 15 shows the result. We can see the transmission in Pilotfish channel is slightly (2dB) more robust. The gain mainly comes from placing control subchannels to both sides of a incumbent channel.

Therefore, we conclude that Pilotfish transmissions in guardband are more robust than Wi-Fi transmissions in incumbent channel when cross-channel interference exists.

5.3 Pilotfish MAC

Clear Channel Assessment (CCA) is the basis of CSMA based protocol. To verify the feasibility of Pilotfish MAC, we conduct experiments to evaluate the CCA performance. We still use cables to set up controlled environment as above. We measured both false negtive and false positive rate with various SNR values. Figure 16 shows that the false rates are very low with $10dB$ or higher SNR. Only when the SNR approachs to marginal value, *e.g.* $5dB$, the false negtive rate increases a little to 20%. Thus, we conclude that the CCA for Pilotfish MAC is robust.

5.4 Minor Issues

We also verified some minor issues using experiments, for example, device mobility and higher modulation density of incumbents.

Our test-bed has a limitation that it is not easy to move the whole Sora system around. Therefore, we connected the antennas and the radios using 2-meter long cables. The experiments were conducted by moving the antennas. We repeated the experiments in above subsections. Since we only moved the antenna in limited space, we only obtained results for a subset of the SNR values. The results were similar to above subsections therefore we do not include them in the paper. This experiments validated that the mobility associated with human movement does not cause problem to Pilotfish.

Finally, we also tried high-density modulation, *i.e.* 16-QAM, for the Wi-Fi transmitters. The high-density modulation lead to a nonflat spectrum of the incumbent signal. However, we validated that it does not make any difference to Pilotfish.

6. Pilotfish APPLICATIONS

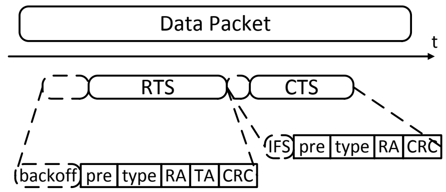

Figure 17: Illustration of control channel RTS/CTS.

In this section, we briefly discuss two applications that Pilotfish can enable to demonstrate the value of Pilotfish.

6.1 Decoupled Control Channel

The first application is to convey Wi-Fi control messages using Pilotfish. In this subsection, we use a simple example to demonstrate the benefits of a decoupled control channel enabled by Pilotfish. As already discussed in [10], in enterprise Wi-Fi networks where downlink scheduling is possible, a decoupled control channel can add important functionality to uplink thereby enabling a lot of interesting applications, such as spectrum efficiency improvement, power efficiency improvement, quality of service, seamless roaming, *etc.*.

In this section, we discuss a simple augment to Wi-Fi's distributed control function (DCF), which is enabled by Pilotfish. The idea is to move RTS/CTS exchange from data channel to control channel, as shown in Figure 17. We call this protocol as control channel RTS/CTS (CCRC). The benefits of CCRC are in multi-folds. First, a successful exchange of RTS/CTS reserves a transmission opportunity. The winning sender can transmit its packet immediately after current data packet, without waiting for the backoff slots. Therefore, the overhead of backoff can be largely saved. Second, benefit from the capability of making reservation, many packet transmissions do not need to rely on random backoff, collisions caused by choosing the same backoff time can be largely reduced. Third, the broadcasting RTS/CTS can mitigate hidden terminal. This feature is usually disabled due to large overhead of RTS/CTS performed in data channel. Fourth, CCRC is backwards compatible with Wi-Fi. We remain the existing control schemes of Wi-Fi in CCRC, therefore CCRC capable devices seamlessly work with legacy Wi-Fi devices, though CCRC capable devices may take advantage of the reservation to get more transmission opportunities.

Simulation Results.

In order to study the benefit of CCRC in larger scale, we conduct NS-3 based simulation. The simulated network includes multiple APs and a varying number of clients that are randomly and uniformly distribted on a 100×100 grid. We simulate a congested network that every node is trying to schedule a large amount of traffic.

Figure 18 shows the throughput gain of CCRC. When RTS/CTS is disabled, CSMA/CA suffers from collisions due to hidden terminals. When RTS/CTS is enabled in data channel, it causes much overhead. CCRC enables RTS/CTS without overhead, therefore consistently outperform both schemes. As the number of nodes increases, CCRC achieves more throughput gain because it mitigates more hidden terminals as well as reduces more contention overhead. As a result, CCRC's throughput gain is up to $3.3\times$ over CSMA/CA and $3.7\times$ over RTS/CTS.

6.2 Interference-Free Zigbee

The other application is using Pilotfish to realize an interference-free Zigbee system in 2.4GHz unlicensed band. As mainly working in the shared unlicensed band, Zigbee suffers a lot from Wi-Fi interference. With the help of Pilotfish's Nulled Decoding technique,

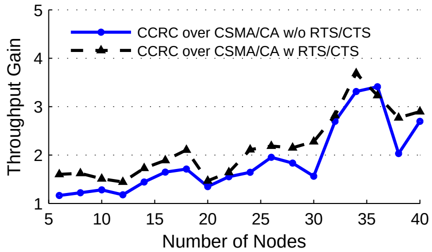

Figure 18: Simulation study. The throughput gain of CCRC over CSMA/CA with and without RTS/CTS.

we will be able to develop a new Zigbee system that nulls Wi-Fi interference.

7. RELATED WORK

The guardband and adjacent channel interference has been extensively studied by Yang, *et. al.* [22] where the observation is that the current fixed guardband does not entirely solve the adjacent channel interference problem. Therefore a variable size guardband is proposed. Chintalapudi, *et. al.* [9] proposes to apply sharp filter on data channel and largely reduces guardband size. The filtered data channel is totally different from the current OFDM PHY in Wi-Fi, therefore is not a target for our work.

Explicit control channels have been proposed in literatures [10, 14,21,23]. Kyasanur, *et. al.* [14] proposes the similar idea as CCRC by allocating a control channel in a distant frequency of $900MHz$ ISM band. Although significant improvement has been shown as the same as CCRC, it is difficult to deploy in practice since the freqency is not specified in Wi-Fi. Zhang, *et. al.* [23], exploits a feedback control to send symbol-level acknowledgement to improve the error recovery performance on lossy wireless links, it also faces the problem of finding an additional frequency band for the control channel. In-band control channels [10, 21] does not require additional spectrum, but they introduce interference to the data channel which eventually causes packet loss.

8. CONCLUSION

In this paper, we present the Pilotfish system which realizes independent communication in guardband whitespace. Empirical results based on a prototype validated the design and techniques. Since Pilotfish turns the wasted guardband frequencies into new commmunication channels, we believe it will bring great value given spectrum resource is so scarce and expensive today.

Acknowledgement

We would like to thank our shepherd, Prof. Vijay Subramanian for his help with the final version. We also thank the W&N group members of MSRA and the anonymous reviewers for their insightful and constructive comments.

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