ShiftFFT: An Efficient Approach to Mitigate Adjacent Channel Interference in OFDM Systems

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ABSTRACT

Adjacent channel interference (ACI) in wireless systems is commonly mitigated through the use of guard bands and filters. Guard bands are not used for any transmissions and are therefore wasted spectrum. The use of sharp filters can reduce the size of required guard bands but they are costly and often not present in devices that are already deployed. We focus on OFDM wireless systems, which form the basis for almost all modern wireless networks, and propose a novel technique called ShiftFFT that can be deployed at an OFDM receiver to mitigate ACI from legacy OFDM transmitters. ShiftFFT exploits the presence of over-provisioned cyclic prefixes in most OFDM wireless standards to optimize the starting time of the FFT operation at the receiver, which we show to have significant potential to reduce the amount of guard band required to avoid ACI and thereby enable efficient spectrum use. We evaluate ShiftFFT with a SDR testbed and using simulations across diverse settings, and show that using it can significantly reduce the guard band required by at least 10MHz in most cases while maintaining the same packet error rate performance.

1. INTRODUCTION

Spectrum is a scarce resource, carefully managed by regulatory agencies across the world. It is divided into smaller chunks (bands or channels), and assigned to different classes of users. However, no transmitter is perfect, and every transmission leaks some signal outside of its intended transmission channel. The maximum power level of such leakage, often called out-of-band or adjacent channel interference (ACI), is also regulated by imposing a transmit spectrum mask that is realized using a transmit filter. The spectrum mask defines the power distribution permitted across each channel and requires the signal to be attenuated to certain power levels at defined frequency offsets. Fig. 1 shows the transmit spectrum mask specified for IEEE 802.11a. On one hand, if the imposed spectral mask is too sharp, filters required to achieve this are expensive, increasing the cost of transmitters. On the other hand, if ACI is too high, it hurts transmissions on adjacent channels.

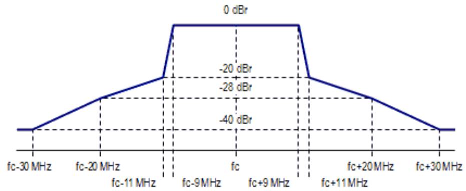

Figure 1: The IEEE 802.11a standard defines a transmit spectrum mask that allows the signal to be unmodified at f_c (center frequency), less than -20dBr at frequencies beyond $f_c \pm 11$Mhz, less than -28dBr at frequencies beyond $f_c \pm 20$Mhz and less than -40dBr at frequencies beyond $f_c \pm 30$Mhz.

The usual way to limit the harmful effect of ACI is to specify a transmit spectrum mask *and also* leave empty spectrum chunks, called guard bands, on both sides of the transmitted signal. Using wide guard bands allows the use of low-cost transmit side filters but it comes at the expense of inefficient spectrum use as guard bands are essentially unused spectrum. To illustrate this consider the simple example of a legacy WiFi transmitter. At a distance of 8 meters from the transmitter, we receive the transmitted signal at 30dB, which is a typical SNR for a high-quality WiFi reception. WiFi spectral mask imposes a limit of approximately -20dB out-of-band interference. In this case the interference at the edge of the adjacent channel will be 10 dB, which significantly raises the noise floor and impedes reception on that channel. For this reason, WiFi (e.g., 802.11a) mandates using 11 (out of 64) subcarriers for guard band between channels, resulting in almost 20% unlicensed spectrum in 5 GHz wasted in the name of guard bands. More sophisticated and costly transmitters will implement better filters and reduce waste in guard bands. For example, current TV white space devices have to achieve -55 dB out-of-band filtering to meet FCC specifications. But many legacy wireless communications standards are far from this threshold, including WiFi, LTE mobile clients and DVB-T transmitters. Imposing more stringent spectral requirements is not always practical, as it will increase the cost of a device and also cannot be applied to devices that are already deployed.

In this paper we propose a novel way to design a wireless receiver, called ShiftFFT, which mitigates out-of-band interference from a legacy transmitter in an adjacent channel *without modifying the transmitter*. Our technique can mitigate interference from legacy transmitters based on the OFDM physical layer (PHY), which includes many current wireless standards such as WiFi, LTE and DVB-T. ShiftFFT can be applied to any OFDM standard, and leverages the observation that interference captured by an OFDM receiver in a subcarrier depends on the actual point at which the receiver performs the FFT operation. Since each OFDM symbol is preceded by a cyclic prefix (CP), the receiver has some flexibility to shift the starting point of the FFT operation without affecting its ability to decode the signal of interest, as long as it stays within

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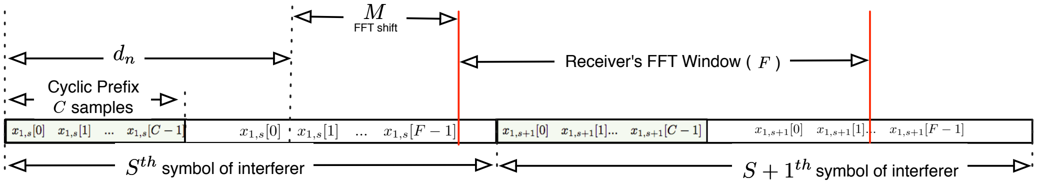


Figure 2: Illustration of receiver side FFT operation with shift M when transmitter n in an adjacent channel has a time offset $d_n > C$, where C is the cyclic prefix.

the duration of the CP. By carefully choosing the position of the starting point of the FFT, we can significantly reduce the interference from an OFDM transmitter in an adjacent channel. We exploit the fact that in most of the OFDM PHY designs the size of cyclic prefix is largely over-provisioned, and so we have some inherent flexibility to move the start of the FFT operation without affecting the receiver's performance. An appealing aspect of our technique is that the proposed changes are local to the receiver, and such a receiver can still be used to receive signals from commodity transmitters, making it backward compatible and easily deployable.

In summary, our key contributions are as follows: (i) We propose a novel technique called ShiftFFT that is able to post-process a received signal and decrease adjacent channel interference without modifying the transmitter; this in turn reduces the guard band required and enables efficient spectrum use. ShiftFFT is practical in that it is enabled by an estimation algorithm to find the FFT start position that can keep packet errors low. (ii) We evaluate the effectiveness of ShiftFFT in terms of guard band reduction in multiple settings (different modulation schemes, number of interferers, etc.), using both simulations and a SDR testbed. Our results show that using ShiftFFT can significantly reduce the guard band required by at least 10MHz in most cases while maintaining the same packet error rate performance.

2. SHIFTFFT

2.1 Background and Key Insight

In OFDM PHY based systems, strict time synchronization is a mandatory requirement to maintain the orthogonality among the subcarriers. When the temporal offset between different users exceeds the duration of CP, the orthogonality between the subcarriers is lost and leads to ACI [5]. It may not always be possible to maintain time synchronization among all users sharing the spectrum. For instance, consider a set of users associated to a set of base stations (BSs). Any temporal offset between the users and the BS they are associated with can be eliminated when the users delay their transmissions by a duration that is computed and provided by the BS. This way, a BS can keep all users associated with it in sync. But users that are not associated with a BS but are still within the range of the BS cannot benefit from this and may have temporal offset, which causes ACI at the BS. The ACI is more severe when the power of the interference signal increases.

We now analyze the characteristics of such ACI caused by temporal offsets among users sharing the spectrum.

Let vector $X_{n,s} = (X_{n,s}[0], \cdots, X_{n,s}[F-1])$ denote a complex vector representing the s^{th} OFDM symbol transmitted by the n^{th} user in frequency domain with F subcarriers. The time-domain representation is given by
$x_{n,s} = (x_{n,s}[0], \cdots, x_{n,s}[F-1])$, where,
$x_{n,s}[t] = \frac{1}{F}\sum_{f=0}^{F-1} X_{n,s}[f]e^{i2\pi ft/F}$ for $0 \le t < F$.

The time-domain signal with a cyclic prefix of size C transmitted by node n is given as follows,

$$x'_{n,s}[t] = \begin{cases} x_{n,s}[F-C+t] & \text{for } 0 \le \text{t} < \text{C}. \\ x_{n,s}[t-C] & \text{for C} \le \text{t} < \text{F+C}. \end{cases}$$

Let d_n be the timing offset between transmitter n and a receiver. The frequency domain representation of the received symbol is given by,

$$\tilde{X}_{n,s}[f] = \sum_{t=0}^{F-1} x'_{n,s}[t+d_n]e^{-i2\pi ft/F}$$

When the reception is synchronous, i.e., $d_n = 0$, we get $\tilde{X}_{n,s}[f] = X_{n,s}[f]$. In case of asynchronous reception, the signal can still be received when the time offset $d_n \le C$, albeit, with a phase shift. It can be easily verified that, for a shifted periodic sequence, we get $\tilde{X}_{n,s}[f] = X_{n,s}[f]e^{-i2\pi fd_n/F}$.

When the timing offset $d_n > C$, subcarriers are no longer orthogonal. Let M be the number of samples that can be skipped before the FFT window is sampled. In particular, with the FFT window as shown in Fig. 2, the frequency domain signal is given by,

$$\begin{aligned}\tilde{X}_{n,s}[f] = &\sum_{t=d_n+M}^{M+F+C-1} x'_{n,s}[t]e^{-i2\pi f(t-d_n-M)/F} \\ &+ \sum_{t=M}^{d_n+M-C-1} x'_{n,s+1}[t]e^{-i2\pi f(t+C-d_n-M)/F}\end{aligned} \tag{1}$$

which can be expanded to:

$$\begin{aligned}\tilde{X}_{n,s}[f] =& \frac{1}{F}(F+C-d_n-M)X_{n,s}[f]e^{i2\pi fd_n/F} \\ &+ \frac{1}{F}(d_n+M-C)X_{n,s+1}[f]e^{i2\pi f(d_n+M-C)/F} \\ &+ \frac{1}{F}e^{i\pi f(d_n+M-C+1)/F} \\ &\sum_{u=0,u\neq f}^{F-1} X_{n,s}[u]\frac{sin(\pi(C-d_n-M)(u-f)/F)}{sin(\pi(u-f)/F)} \\ &\times e^{i\pi(d_n+M+C-1)u/F} \\ &+ \frac{1}{F}e^{i\pi f(d_n+M-C+1)/F} \\ &\sum_{u=0,u\neq f}^{F-1} X_{n,s+1}[u]\frac{sin(\pi(d_n+M-C)(u-f)/F)}{sin(\pi(u-f)/F)} \\ &\times e^{i\pi(d_n+M-C-1)u/F}\end{aligned} \tag{2}$$

Interestingly, it can be seen from Eq. 2 that the interference component due to this temporal offset is sinusoidal in nature. This

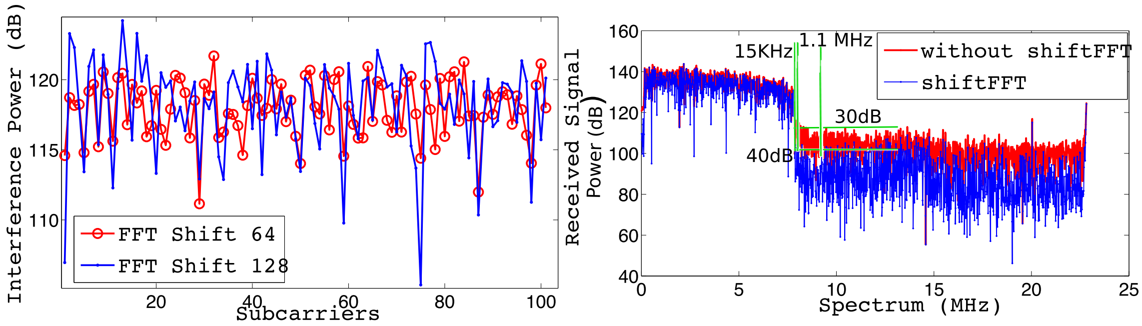


Figure 3: (a) ACI power at two different FFT shifts; (b) Illustration of ACI and guard band reduction with ShiftFFT.

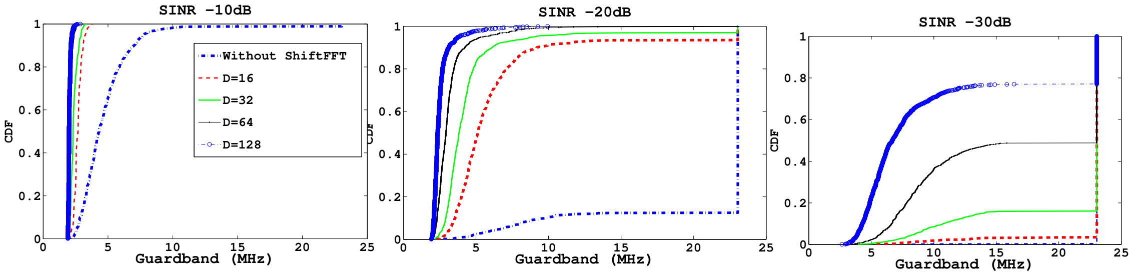
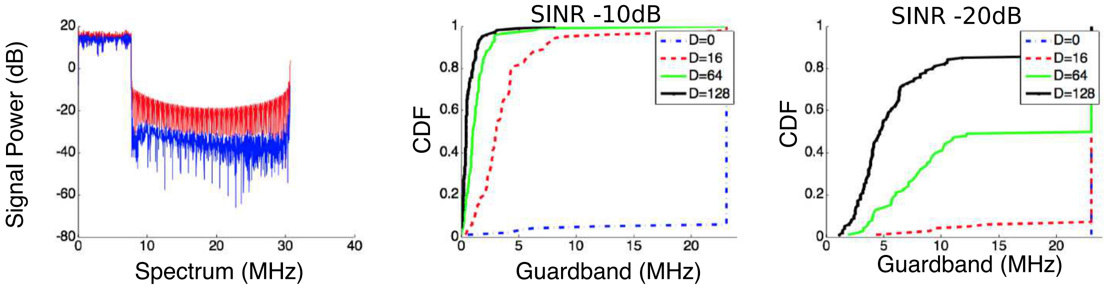


Figure 4: Required guard band with and without using ShiftFFT in the case with a single adjacent channel interferer and QPSK modulation with 3/4 coding rate. For ShiftFFT, the effect of using different CP sizes (D) is shown — higher the CP size greater the number of starting positions for FFT.



(a) (b) (c)

Figure 5: (a) Nature of ACI with two adjacent channel interferers and the benefit of using ShiftFFT (shown in blue); (b-c) Guard band required with and without ShiftFFT in presence of two adjacent channel interferers in different SINR conditions.

shows that the amplitude and phase of the interference would vary with the starting point of the FFT window M and more importantly, there would be an FFT shift where the interference on each subcarrier would be minimal. This behavior can be seen in Fig. 3(a), which shows the power of interference due to a transmission on an adjacent channel for a set of subcarriers and for two different FFT shifts with $M = 64$, and $M = 128$. To clarify, FFT shift of 64 (similarly 128 or any other shift) indicates that the OFDM symbol is sampled starting from the 64th sample or at 2.08 μs after the start of the transmission in the intended channel of the receiver (and not the transmission in adjacent channel). In Fig. 3a, we can see that for subcarrier 75 using an FFT shift of 128 would reduce the interference impact by about 10dB compared to that with a FFT shift of 64.

2.2 Basic Idea

Our approach named ShiftFFT exploits the sinusoidal nature of ACI due to temporal offsets and essentially tried to identify the FFT shift that minimizes ACI. We use LTE PHY as a concrete setting to elaborate the idea behind ShiftFFT. In LTE, each OFDM symbol is made of 2192 samples, which consists of 2048 samples of signal (66.7 μs) and 144 samples of CP (4.69 μs). The receiver can shift the starting point of the FFT operation without having any adverse effect on the signal reception, as long as it stays within the duration of the CP. Assuming 20MHz bandwidth, the size of the FFT block is 2048 and there are several choices for the starting point from which the OFDM symbol can be sampled. The starting point for the FFT operation can vary from 1 to 144 samples or until 4.69μs since the start of the transmission. Some samples at the beginning of the CP have to accommodate for the delay spread in the environment and will be ignored while choosing various possible different FFT starting points (or equivalently, FFT windows).

The benefit with ShiftFFT in mitigating ACI by choosing the optimal FFT shift for each subcarrier is illustrated in Fig. 3b. In this example, the transmitter on adjacent channel uses an 8MHz channel for transmission. The spectrum mask realized using ShiftFFT (shown in blue) is very sharp compared to the vanilla case of not using any ACI mitigation mechanism (shown in red). We see that with

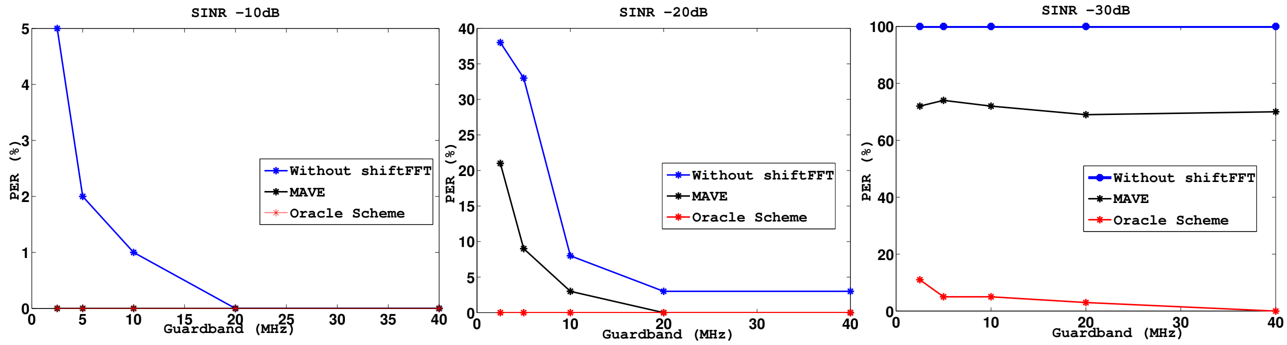


Figure 6: PER performance using two variants of ShiftFFT (Oracle and MAVE): single adjacent channel interferer, QPSK with 3/4 coding rate, varying guard band and SINR values.

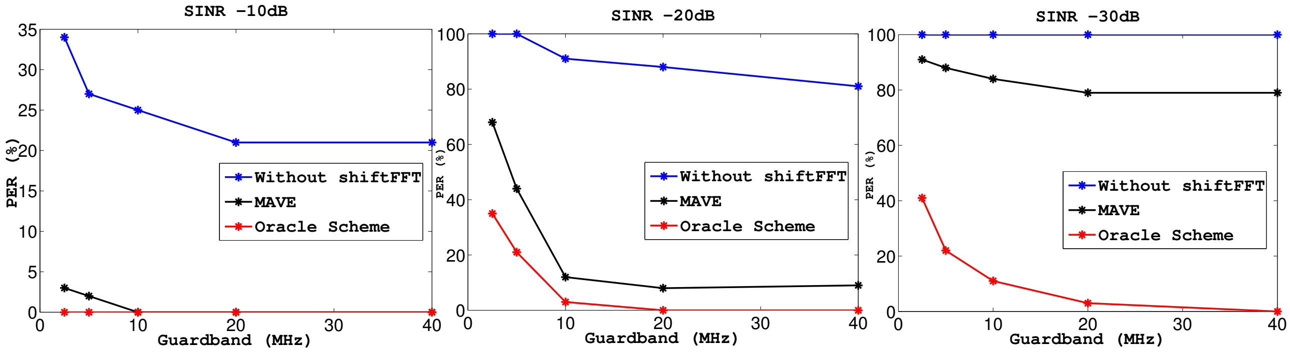


Figure 7: PER performance using two variants of ShiftFFT (Oracle and MAVE): single adjacent channel interferer, 64-QAM with 3/4 coding rate, varying guard band and SINR values.

ShiftFFT the required guard band is significantly reduced to just 15KHz to achieve a ACI threshold of -30dB (and to about 1.1MHz to keep ACI to at most -40dB). This indicates how ShiftFFT can enable packing transmissions more tightly and help achieve better spectral efficiency.

Oracle Scheme: In the above description, it is assumed that the interference is known to the receiver. With this information, the receiver can compute the optimal FFT shifts of the received signal for each subcarrier to minimize the effects of ACI. The result of using such an oracle scheme is illustrated (in blue) in Fig. 3b. The oracle scheme provides us with an idea of the scope of interference mitigation possible with ShiftFFT approach and we use it as a benchmark to evaluate a more practical scheme, described next.

2.3 Practical Algorithm

In reality, a receiver would not be able to distinguish between the received signal and the interference. And it is not simple to identify the optimal FFT shift for each subcarrier in the absence of any knowledge of the interference. This is because a change in amplitude or phase at different FFT shifts could be due to the effect of both the signal and the interference at the subcarrier. To address this issue, we came up with a metric called MAVE, which we show to perform reasonably well in identifying the right FFT shifts.

Minimum Average Vector Error (MAVE): The intuition behind MAVE is that, since the interference is AWGN and the signal remains the same (albeit with a fixed phase shift which can be corrected), the received signal on a subcarrier at different FFT shifts would drift around the actual constellation point used by the transmitted signal of interest. For each subcarrier, MAVE computes the average deviation of the received complex vector from the various possible constellation points for the modulation scheme used, over all the FFT shifts. The constellation point with the minimum deviation is inferred as the actual constellation point used and the FFT shift with the complex vector that has the minimum deviation to that constellation point is chosen as the FFT shift to use for that subcarrier.

3. EVALUATION

We evaluate ShiftFFT using a combination of testbed based experiments and simulations. For experiments, we use a testbed based on Microsoft Sora SDR platforms. Sora [6] is a fully programmable software radio platform that works in conjunction with a commodity PC. We have developed a full fledged OFDM PHY for the receiver and transmitter. The complete OFDM PHY is implemented in Matlab and is used to process the received signal offline. The signal to be transmitted is also generated offline and is stored as IQ data in files. We study the impact of different SINR conditions and using different modulation schemes. A received signal with the required SINR is generated by varying the interference power. In the experiments, samples consisting of 100 packets were prepared under different channel conditions for each guard band configuration and transmitted using the Sora boards. The received signal from the transmitter and the interferers are then processed offline in Matlab.

We use LTE settings in our evaluations. As in LTE, 2048 subcarriers each with a spacing of 15 KHz are used for reception. Each symbol has a duration of 66.7 μs made of 2192 samples of which 144 samples are used for cyclic prefix. One for every 20 subcarriers chosen uniformly is used for pilot correction with a known random pilot signal in that subcarrier. In order to obtain a good channel estimate with ShiftFFT, we perform channel equalization by sending the same preamble twice at the start of each transmission. This process is critical for ShiftFFT since it provides a good channel estimate even in the presence of interference. The overhead due to the additional preamble will be analyzed and optimized in future work.

First, we analyze the size of the guardband required when different durations of CP (16, 32, 64, and 128 samples) are available for ShiftFFT to exploit. The size of the required guard band is defined as the minimum number of subcarriers that are required in between an adjacent channel interferer and the transmitter to achieve a packet error rate (PER) of less than 1%. For a given modulation and coding scheme (which is true for each of our experiments), using PER to define guard band is equivalent to that using interference-to-noise-ratio (INR). Fig. 4 presents required guard bands for different SINR values as CDFs. These results correspond to a case with a single adjacent channel interferer and QPSK modulation scheme with 3/4 coding rate. We see that using ShiftFFT yields significant reduction in the size of the guard band required. In some cases, when ShiftFFT is not used either the guard band required is prohibitively large or communication would not have been possible with a smaller guard band. For example, when SINR is -30dB, the guard band required without ShiftFFT is greater than 20MHz, where as with ShiftFFT around 7 MHz of guard band is sufficient for majority of the cases.

When multiple adjacent channel interferers are present, the nature of ACI remains the same and can still be mitigated by sampling subcarriers at different FFT shifts. To substantiate this point, the collective impact of two interferers using 0-8 MHz on the adjacent channel is shown in Fig. 5a. The guardband required at SINR values -10dB and -20dB in the two interferer case is shown in Fig. 5b-c. The use of ShiftFFT enables communication in these conditions even in the presence of two interferers with less than 10MHz required as guard band in most cases, whereas greater than 20MHz guard band would otherwise be needed. Note that these results with two interferers are the only ones obtained via simulations; rest are from experiments on Sora based testbed.

MAVE: The results presented so far rely on the oracle scheme to indicate the potential of ShiftFFT approach for ACI mitigation and guard band reduction. We now present results with MAVE, a practical scheme for ShiftFFT described in Section 2.3 to estimate the right FFT shift for each subcarrier. For comparison, we include the results with the oracle scheme. We consider a single adjacent channel interferer case and two different modulation and coding schemes: QPSK and 64-QAM, both with 3/4 coding rate. Fig.6 and Fig.7 show the respective results in terms of PER for different SINR values and guard band sizes. Besides demonstrating the effectiveness of ShiftFFT in general, these results also show that MAVE metric yields promising results close to oracle especially for moderate to high SINR conditions. Overall, we can observe that with ShiftFFT the size of guard band required is reduced by at least 10MHz while ensuring the same or better packet error rate performance in almost all cases. Further refinement of MAVE for improved performance in low SINR conditions is an aspect for future work.

4. RELATED WORK

In [5], the authors analytically study the effects of adjacent channel interference on OFDMA based packet transmissions. They also evaluate three mechanisms for mitigating ACI (guard bands, inter-symbol cancellation and cross-symbol cancellation) and conclude that the use of guard band is the most efficient mechanism in the presence of temporal mismatch or frequency offset.

The effect of ACI on IEEE 802.11 networks has been extensively studied [1, 3, 4, 7, 8]. In [7], the authors model and quantify the effects of ACI in IEEE 802.11 networks. They show that when there are limited number of non-overlapping channels and when the co-channel interference is quite severe relative to the ACI effect, using partially overlapping channels is preferred over just using the few non-overlapping channels. They also propose an analytical model which can be used to determine the right circumstances where the use of adjacent channels is justified. The adverse effects of ACI on the carrier sensing mechanism in IEEE 802.11n networks is discussed in [8]. Using extensive experiments, the authors study the effect of ACI in different settings and show that it can cause both exposed and hidden terminal problems, resulting in wasteful use of spectrum.

In [3], using experiments, the authors conclude that even a weak interferer transmitting in the adjacent bands can have a considerable effect on the received signal. The size of guard band recommended to avoid such effects is at least 40 MHz. A recurring conclusion in all these papers is that ACI cannot be avoided unless a sufficiently large guard band between transmissions subject to ACI is used; the latter is undesirable in view of limited amount of spectrum.

WiFi-NC [2] advocates the use of narrow band channels instead of large monolithic channels to improve the spectral efficiency. Frequency guard bands and elliptic filters are used to achieve channel isolation and mitigate ACI. Our proposed ShiftFFT technique can help reduce the size of guard bands required for WiFi-NC.

5. CONCLUSIONS

Adjacent channel interference is commonly mitigated via guard bands or sharp filters. Guard bands result in wastage of spectrum whereas sharp filters are very expensive. In this paper we have proposed a novel wireless receiver ShiftFFT that can mitigate ACI without requiring any changes to the transmitter. We exploit the ability to move the FFT frame along the duration of the cyclic prefix while sampling an OFDM symbol. We observed that the interference varies widely between FFT shifts and choosing the optimal FFT shift for each subcarrier would minimize the effects of ACI. We have proposed MAVE, a practical mechanism to identify the right FFT shift for each subcarrier in the absence of knowledge of interference. Using a Sora testbed based evaluation, we have demonstrated the ability of ShiftFFT in mitigating ACI and necessitating significantly smaller guardbands. Our future work will focus on further assessing robustness of ShiftFFT in practice and confirming its usefulness in a diverse set of use cases, including Wi-Fi, LTE HetNets and TV white space networks.

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