Spectral Efficiency: Using Full-Duplex Techniques & Cognitive Radios

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I. ABSTRACT:

Growing demand for mobile data consumption has emphasized on efficient usage of scarce resources in wireless communications, such as radio spectrum and transmit power. In this paper, we discuss two such efficiency improving techniques, which intend to improve the wireless systems capacity by improving spectral efficiency: single channel Full Duplex (FD) systems and Cognitive Radios (CR). The spectral efficiency advantages of these two techniques are discussed in terms of capacity and Bit Error Rate (BER), along with their implementation challenges. Furthermore, the paper examines results from recent research attempting to integrate both Full Duplex systems and Cognitive Radio technologies into a single system.

II. INTRODUCTION:

With the advent of video streaming services, multiplayer games, online games, live airing of digital content over the air, and mobile TV, the consumption and thus the demand for mobile data has increased exponentially in the recent past. In contrast to this burgeoning demand, the supply of the natural RF resources has remained the same and underutilized in an inefficient way, owing to the generations old spectral auctioning processes, orthogonal access techniques, and the firmly believed dogmas on single channel FD system.

Precisely speaking, present days' so called Full Duplex devices are Half-Duplex (HD) devices, as they can simultaneously transmit and receive only on channels separated either in time, space, frequency or codes. In contrast to this, single channel FD systems or simply FD systems, are capable of transmission and reception on the same physical channel. Compared to these HD devices, their ability to improve spectral efficiency by a factor of 2 makes FD systems very appealing. But this advantage comes at the cost of increased circuit complexity, larger buffer memory and possibly multiple antenna requirement. A FD circuit is far more complex as it uses additional components to achieve better isolation from Self-Interfering (SI) signal. Moreover, FD device's full potential to reduce Packet Loss Ratio (PLR) can only be realized through additional memory to store packets received from increased capacity [1]. It might also necessitate use of multiple antennas to achieve a better SI signal suppression through passive suppression techniques. Lastly, compared to 2X2 MIMO which could double the capacity, FD systems can additionally solve age old hidden-terminal problem, congestion, end-to-end delay problems and Primary User (PU) detection problems in CR [1], as discussed in the later sections of this paper.

Cognitive radios on the other hand are capable of opportunistically identifying and using the unused spectrum resources, to improve the overall system capacity. Furthermore, CR systems' capabilities also enable very quick deployment of communication systems in state of emergencies as they can automatically adapt to the deployed radio environment [2].

In this paper, we study FD systems, CR systems, and their impact on spectral efficiency while using capacity, BER and throughput as the performance measure. Additionally, we also examine the recent development in combining both methods to achieve significantly higher performance improvements. Section 3 of this paper describes the FD systems, advantages of FD systems, and important challenges impeding practical realization of such systems, while discussing various approaches examined by researchers to address these problems. Section 4 and 5 elaborate on SI cancellation techniques and FD Medium Access Control (MAC) techniques. Section 6 briefly explains the CR systems, and its advantages. It also builds on the combination of CR and FD systems, and presents the results of such experiments. Finally Section 7 concludes this paper.

III. FULL DUPLEX WIRELESS COMMUNICATIONS:

As mentioned earlier, FD devices are capable of doubling spectral efficiency by simultaneous transmission and reception on same physical channel, i.e., frequency, time and in certain cases antenna. Thus a FD system receiver faces interference from its own transmitter, called the Self-Interference (SI). The primary challenge in FD systems is that the SI signal is magnitude of orders louder than the signal of interest, thus making it difficult to detect and estimate the signal of interests signal.

While we discuss the SI mitigation techniques in the next section of the paper, understanding additional benefits of employing a FD device underscores the motivation to pursue a FD system. In a FD system, the hidden node terminal problem is suppressed significantly as the receiver node can talk back to the Primary Transmitter on the same frequency, thus informing its busy status to the secondary transmitter, even if the primary transmitter is out of radio range of secondary transmitter. On the other hand, since the Primary Receiver transmits simultaneously during a communication session, the downward packets don't necessarily have to wait or share the resources with any of the upward transmissions or neighboring device's downward transmissions. Thus, network congestion reduces as the ratio of network capacity to single-link capacity approaches unity [1]. Furthermore, simultaneous reception equips the radios with the ability to sense and detect a primary user's presence in a CR environment, while transmitting data.

Contrary to the advantages of a FD system, its ability to simultaneously process two independent Radio Frequency (RF) chains demands a larger buffer to avoid higher PLR, a better processing capability, and tolerance to increased degradation of link due to self-induced interference.

Although spectral efficiency is the performance measure of interest, plethora of quantified results compare HD and FD systems in terms of capacity, throughput, outage probability (OP) and BER, which can easily be translated to spectral efficiency [1]. While a high throughput, low OP and BER symbolize more data transferred, and thus a higher spectral efficiency, a low throughput/capacity, and a high OP or BER indicate poor performance in terms of spectral efficiency. In terms of capacity, [11] establishes that there is a clear trade-off between FD benefits and acceptable SI levels compared to a HD systems. More precisely the Amplify and forward (AF) mode of FD relaying systems' performance is independent of SNR, if the SI is well below the noise floor of the system. But compared to a HD system, the performance degrades if SI is greater than noise floor, as SI contributes to deterioration the Received (Rx) Signal [1]. On the other hand, a FD system's capacity in Decode and Forward (DF) mode remains uneffaced by changes in SNR, but is highly dependent on the buffer size of the device [1]. And in terms of BER, AF mode with beam forming in FD systems is superior at SNRs lower than 5dB, due to low SI as a result of less power utilized for transmission, compared to a HD systems. But the same systems performance is but inferior beyond 15dB due to presence of high SI signal. [1]

IV. SELF INTERFERENCE CANCELLATION TECHNIQUES

The large power difference between SI signal and the Received (Rx) signal is the single major challenge in developing a FD system. Several approaches were proposed to mitigate the effects of SI including passive interference cancellation techniques, and active cancellation techniques [1]. All these techniques can be organized into 3 major categories, depending on the approach followed. They are Passive Suppression, Active Cancellation, and Impairments Imposed on SI Cancellation. As most techniques cannot achieve a cancellation beyond 50~60 dB, a combination of such techniques is required to achieve the necessary 95dB suppression, for a 0dbm transmitted (Tx) signal. [1] Furthermore, we would also see that not all techniques' combination reduce SI signal monotonically, as shown by [3]. In this paper we discuss certain important SI mitigation techniques in the following subsections.

A. <u>PASSIVE SUPPRESSION:</u>

Passive cancellation techniques rely on physical devices and medium characteristics, such as circulators, antenna placement, directions and distance between antennas, to reduce the power of the SI signal in the Rx signal. As an example, [7] proposes an antenna cancellation technique, where the transmitter places an additional antenna at a distance that is off by a multiple of $\lambda/2$, to destructively superimpose the two transmitted signals at the receiver antenna (RA), Here λ is the wavelength of the center frequency. This approach when tested on 802.15.4 radios achieved a 30dB SI cancellation. [12] on the other hand takes advantage of the directional properties of antennas to achieve SI cancellations of up to 48dB in an outdoor-indoor relay system, when the antennas are placed in opposite directions. [13] reduces the amount of SI signal power by minimizing the main lobe alignment of TA and RA.

While passive suppression provides an average of ~30dB cancellation, it is not sufficient for 802.11 requirements with >0dBm transmission power and a mandatory -95dBM noise floor. It is apparent that infeasible distances are required to reduce the SI signal below noise floor, using path loss as the only factor of SI cancellation between TA and RA. Additionally, apart from multiple antenna requirements, as bandwidth of the signal increases, the phase spread to cancel the corresponding frequencies also vary widely. Thus such techniques are feasible only for narrow band signals. Furthermore for widely used modulations like OFDM, an estimate for a subcarrier may differ significantly from the other subcarrier's estimate [7].

B. ACTIVE CANCELLATION:

As Passive cancellation techniques are not sufficient to subside the SI signal below noise floor to decode the Rx signal, we resort to active cancelation techniques. Among the three common techniques: analog cancellation, digital cancellation and MIMO aided aggregate analog and digital cancellation techniques, this paper discusses the relatively important analog cancellation and digital cancellation in the following sub sections, owing to the construction of the current RF systems.

Most RF chains downconvert RF signal to baseband signal and sample baseband signal at a realistic Nyquist Criteria using commercial ADC chips. Even after passive suppression, the baseband signal would be dominated by the SI signal (or even saturate ADC), thus making detection and sampling of the intended Rx signal merely impossible. This can be mitigated using analog cancellation techniques, which produce an inverse signal- either in baseband or RF range, and then add it to the Rx signal contaminated with SI. This reduces the SI component in the Rx signal, and thus spreads the Rx signal's range across larger ADC's range. The inverse signal could either be added before RF mixer stage (pre-mixer schemes) or at the baseband signal, after the RF mixer (post-mixer) scheme. The initial work by [10] proposes a balanced-unbalanced (Balun) based circuit to generate an inverse of the SI signal from the knowledge of the transmitted signal. The inverse signal is then subjected to variable attenuation and variable phase difference and then added back to the Rx signal before the RF mixer at receiver. Although theoretically Balun could inverse signals of very large bandwidth, non-linear frequency response stemming from practical design limits cancellation of SI to an additional 15dB in a 100MHz signal compared to a traditional phase offset cancellation techniques, by optimizing attenuation and delay to minimize the energy difference between the inverse signal and the Rx signal. Although several analog works have demonstrated a typical SI cancellation of 45dB, hardware imperfections due non-linear behavior and the complexity of circuit typically limit going beyond the mentioned cancellation range.

Digital cancellation rescues the Rx signal by estimating and reproducing the SI channel samples, which are then subtracted from the baseband Rx signal's samples. The performance of digital cancellation is based on how good an estimate of channel degradation can be obtained. As we see, [3] models the amount of cancellation in terms of SI channel power. The work also deduced that as SI power increases, digital cancellation techniques performs better due more accurate estimates of the SI channel and degrade as SI Power reduces. Additionally, the model also claims that digital cancellation should be applied with caution, as cascading digital cancellation after analog cancellation doesn't always improve the performance, and surprisingly it could also deteriorate the Rx signal [3]. Furthermore they proved the validity of the same through the distribution of the experimental data driven model of SI channel, which resembled Rician distribution with high K-factor before applying analog cancelation technique and with low K-factor after cancellation. On the other hand [7], modelled SI channel as Linear Time Invariant (LTI) and generated an equivalent Finite Impulse Response (FIR) filter and convolved the Rx signal (after analog cancellation) with this filter.
Although digital filter could potentially eliminate any residual SI component in the Rx signal, given a proper estimate of the channel, an error in SI channel estimate could potentially worsen the Rx signal after analog cancellation. Thus, digital cancellation is highly vulnerable to SI channel estimation error. Furthermore, in a mobile environment, continuous monitoring of the environment is required to calculate accurate SI channel estimate.

V. FULL-DUPPLEX MEDIUM ACCESS CONTROL (FD MAC)

A FD system compatible MAC is equivalently important to take advantage of the second available channel, solve hidden terminal, congestion and end-to-end delay problems. While [7] claims to have introduced first real-time FD functional MAC, designing a FD MAC remains still a challenge because of three main reasons. Firstly, when a node is transmitting in FD mode, receiving a data with zero to little information about channel estimates would not aid the process of decoding at the receiver. Secondly while a node is receiving data, initiating a transmission could momentarily cause SI on the receiver. Lastly, identifying opportunities to simultaneously transmit and receive in an asymmetric network (containing HD nodes) while balancing fairness is a challenge. In [7, 6] a bust-tone based MAC was created , which send a dummy signal to avoid hidden terminal problem, Some other crucial factors to be considered while designing FD MAC protocols are, backward compatibility with existing systems and optimizing energy consumption (as a simple busy tone transmission would drain battery much quickly).

VI. COGNITIVE RADIOS AND FULL DUPLEX COGNITIVE RADIOS

Traditional splicing of resources into orthogonal bock is an inefficient method, as these resource blocks are often underutilized. Cognitive radio's capability to identify such underused resources, and use them without interfering with Primary Users (PU- those having the first claim to licensed frequencies band) demonstrates the scope to improve overall systems spectra efficiency directly. Additionally, the reconfigurability of a CR allows to mitigate fading by moving to another resource block [2].

A typical cognitive radio requires two major functionalities: cognition to sense the wireless environment around itself and reconfigurability to change/adapt its operating parameters to the calculated parameters. While various wide band spectrum sensing techniques like energy detection, feature detection, matched filtering and others enable the radio to get a sense of its environment, appropriate MAC layer protocols help in configuring the radio to the best available resource block. Furthermore, MAC layer protocols are also necessary to continuously change the operating parameters upon detecting any claims by the primary user (PU) and to manage the interference and competition among the secondary users (SU). In addition to the above two methods, a CR network might comprise of multiple independent SU networks, probably controlled by a Spectrum Broker. Typically all the CRs come under either Spectrum under-lay or Spectrum over-lay models of spectrum sharing. [2].

A. SPECTRUM SENSING:

Whilst there are several kinds of spectrum sensing techniques like feature detectors, energy detectors, matched filtering, coherent detection, this section focusses mainly on energy detectors and their application in FD systems.

Energy detectors are the most simple, easily implementable spectrum sensing techniques requiring no prior information. Detection of PU is based on a detection statistic (T): average energy over N samples. When the detection statistic T is greater than a predetermined threshold, it is hypothesized as presence of a PU and when it falls short of the threshold as the absence of FD [2]. While the performance of the estimator is sensitive to the threshold, various adaptive thresholding based algorithms have proposed [2].

While Cognitive Radios do improve spectral efficiency, it comes at the cost of constant sensing overhead. Adding a FD capability to CR is actively considered to reduce sensing overhead. In [9], the performance of energy detector based PU detection in a Full Duplex Cognitive Radio (FDCR) networks is examined in terms of the detection performance in the presence of SI channel, advantages of using multiple antennas (but a single transceiver) over sharing a single antenna for transmission and sensing purposes. While the results clearly demonstrate an increase in probability of missed alarms in FD mode during transmission, a FD SU with different antennas performs better than a FD SU node that is sharing the same antenna for transmitting and receiving, due to higher residual SI induced distortion. Additionally, by using a longer sensing duration the effects of SI distortion could be substantially reduced to that of a HD mode SU.

B. RECONFIGURABIITY:

The ability to adapt the parameters like power, frequency and bandwidth quickly in a constantly changing radio environment determines the success of the SU communications. Such abilities do typically stem from MAC protocols, hand-off techniques.

MAC protocol establishes the rules for users on how to access resources such as spectrum, power time etc. Designing a MAC for CR networks requires meticulous understanding of the dynamics of a CR network ranging spectrum hand-off techniques from between PU and SU to among SUs to control interference. Several MAC protocols have been proposed as seen in [2] ranging from Markov chain based approach to distance-dependent MAC.

In [8, 10], the proposed asynchronous Multi-Channel Full Duplex MAC protocol for cognitive radios demonstrates and compares the throughput performance over a single channel and block of channels in terms of sensing window and transmission power. The results dictate the superiority of FD-MAC over HD-MAC. Furthermore, the work also proves existence of an optimal transmit power to achieve maximum possible throughput.

VII. CONCLUSION:

The spectral advantages of Full Duplex systems over HD systems has be studied in terms of capacity and BER improvement. The spectral efficiency advantages of using a Cognitive Radio (CR) have also been studied from the perspective of sensing/ PU detection. Additionally, the benefits of employing CR techniques, such as energy detector based spectrum sensing and associated MAC protocols in FD mode have been studied, and the results are compared with respect to HD systems. While the FD and CR results assert an improved performance individually, combing both the techniques do show promising results in improving spectral efficiency.

VIII. REFERENCES:

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