Exploring the Potential for Full-Duplex in Legacy LTE systems

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***Abstract*—With the growing demand for increased spectral efficiencies, there has been renewed interest in enabling full-duplex communications. However, existing approaches to enable full-duplex require a clean-slate approach to address the key challenge in full-duplex, namely self-interference suppression. This serves as a big deterrent to enabling full-duplex in existing cellular networks. Towards our vision of enabling full-duplex in legacy cellular, specifically LTE networks, with no modifications to existing hardware at BS and client as well as technology specific industry standards, we present the design of our experimental system *FD-LTE*, that incorporates a combination of passive SI cancellation schemes, with legacy LTE half-duplex BS and client devices. We build a prototype of *FD-LTE*, integrate it with LTE's evolved packet core and conduct over-the-air experiments to explore the feasibility and potential for full-duplex with legacy LTE networks. We report promising experimental results from *FD-LTE*, which currently applies to scenarios with limited ranges that is typical of small cells.**

I. Introduction

The proliferation of smart devices and the resulting exponential growth in data traffic has increased the need to support higher capacity in wireless cellular networks. The cellular industry is envisioning an increase in network capacity by a large factor (extreme accounts put this requirement as a factor of 1000 by 2020) to meet this traffic demand. Enhancements along three dimensions are envisioned in realizing this large gain factor: (i) increased bandwidth, (ii) small cells for increased spatial reuse, and (iii) increasing the spectral utilization of given bandwidth through sophisticated physical layer techniques. While the benefits from the first dimension are direct, they are also limited due to the scarce availability of spectrum. The second dimension of deploying smaller cells is gaining momentum. However, this incurs higher capital and operational expenses for the operators, not to mention the challenge of backhauling the data from the small cells. Hence, small cells cannot replace an entire macrocell network, but will be targeted for specific scenarios such as urban hot-spots, at least for initial deployments. This brings us to the final dimension, where a lot of research has gone into developing sophisticated techniques like MU-MIMO [7], CoMP (coordinated multipoint transmission), etc. that increase the spectral efficiency of the system. Although easier to realize compared to the first two dimensions, unfortunately, the gains from these new features and enhancements in 3GPP LTE are fairly modest ($\approx 10-30\%$) compared to those from the first two dimensions. This raises the question whether there exist any other features in the third dimension that can help boost the spectral efficiency of the system without incurring the limitations of the first two dimensions. This brings us to *full-duplex for legacy LTE systems*.

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Full-duplex is the process of sending and receiving data at a node simultaneously on the same time and frequency resource. In doing so, the receive signal at the node receives direct interference (called self-interference) from the transmit signal at the same node. Given the co-location of the interfering source compared to the farther desired transmission source, this would completely drown the received signal in noise, rendering its decoding improbable. Thus, the key challenge in realizing a full-duplex system has always been the issue of self-interference and how to suppress it in order to enable bi-directional communication. For this reason, all existing cellular systems are built half-duplex from ground up. Recently, there has been renewed interest in the research community [8], [11], [12], [13], [14], [16] in addressing the self-interference (SI) suppression problem to enable full-duplex. Various methods have been explored in realizing the desired level of SI suppression to enable full-duplex communication over WiFi. However, these approaches realize full-duplex from ground up. They rely on analog and digital cancellation techniques that require changes to the hardware and hence demonstrate full-duplex over SDR platforms.

The key question we ask in this work is: *is it possible to enable full-duplex in legacy LTE systems?*, thereby helping double the spectral efficiency of the network. If one were to build LTE from scratch, then base stations and clients can be designed with full-duplex in mind similar to existing approaches [8], [11], [12], [13], [14], [16]. However, this would require all existing base stations and client hardware to be replaced to avail the full-duplexing capability, which is impractical and infeasible. Hence, the key constraint that we would like to work with is to enable full-duplex in a *legacy* LTE system, which neither requires the existing BS or client hardware to be changed, nor the standard to be modified. In other words, the focus here is to see if we could *retro-fit full-duplex to legacy LTE systems*, which is extremely vital to the adoption of full-duplex commercially.

Several challenges arise in realizing the above vision: (i) Since we require that the base station hardware does not change, we cannot leverage digital cancellation techniques for SI suppression and would be restricted to analog cancellation. Is analog cancellation even sufficient to realize full-duplex,

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since otherwise full-duplex would not be possible? (ii) Even if analog cancellation is sufficient, what SI suppression methods need to be leveraged and how can they be realized outside of the base station with its existing hardware? and (iii) How to enable full-duplex in a transparent manner with half-duplex legacy clients without any major modifications to the standard?

Towards addressing these challenges, we present the design of a system called *FD-LTE* that is capable of full-duplex transmission/reception in the same band for downlink and uplink, thereby allowing us to experimentally explore the potential for full-duplex in legacy LTE systems. *FD-LTE* uses only a single antenna port from a conventional half-duplex LTE base station, separates the transmission and reception paths, converts the downlink and uplink frequency bands into a single band, and employs a combination of multiple analog cancellation techniques to provide the desired level of isolation between the transmit and receive antennas. *FD-LTE* also incorporates an intelligent configuration of downlink and uplink spectral bands for the clients, wherein the spectral configuration of some clients are made to be the exact opposite of that of others. This enables full-duplex communication with legacy half-duplex clients through suitable client pairing that does not require any modification to the standards.

We have realized a working prototype of *FD-LTE* and have conducted over the air full-duplex communication with our LTE test-bed. The design incorporates a 3GPP Release 9 LTE compliant prototype base station from NEC, a full-duplex enabler circuit comprising of antenna cancellation, RF shielding and frequency converters, a full integration of the full-duplex LTE base station with the evolved packet core, and finally an LTE client with a full-duplex enabler circuit. Our experimental evaluations are promising and reveal that in both indoor and outdoor environments, appropriate combination of analog SI suppression mechanisms can provide large amounts of SI suppression and enable FD operation in small cell LTE systems. We also show that *FD-LTE* can provide FD gains of 20-40% with a client range of 10-20 m with respect to the BS, that is typical of indoor (femto) small cell sizes.

In summary, the contributions of our work are as follows.

- We show that analog cancellation techniques can be sufficient in certain scenarios (like small cells) to enable full-duplex with legacy LTE systems.
- We present *FD-LTE*, an experimental system, whose simple design allows us to retro-fit full-duplexing capability to legacy LTE BS without changing its current hardware, while allowing for transparent operation with half-duplex legacy LTE clients.
- We build a working prototype of *FD-LTE* with commercial LTE BS, clients and enhanced packet core network and conduct over-the-air experiments to explore the potential for full-duplex with legacy LTE systems.

II. Background and Related Work

LTE. The increased demand for higher capacity has influenced the design of next generation wireless communication systems such as 4G LTE (long term evolution). The design of LTE has focused on achieving high peak transmission rates (100 Mbps in downlink and 50 Mbps in uplink), better spectral efficiency, and multiple channel bandwidths (1.25 –20 Mhz). Orthogonal frequency division multiplexing (OFDM) is used as the PHY technology to achieve these goals in standards such as LTE, IEEE 802.11 (WiFi), IEEE 802.16 (WiMAX), and broadcast systems (Digital Audio/Video Broadcast DAB/DVB). Advances in physical layer components have allowed the use of OFDM technology in LTE. LTE can work in FDD (frequency division duplex) or TDD (time division duplex) mode; however, except for a handful of countries (mainly China) who have considered deployment of TD-LTE, the mainstream deployment is being pursued in the FDD operational mode. Both FDD and TDD are half-duplex operational modes. In TDD operation, the transmission time in the uplink and downlink are separated in a frame. In FDD operation the downlink transmission from the base station to the users occurs in a different band than the uplink transmission from the users to the base station, hence it is possible to have both uplink and downlink frame transmitted simultaneously. For example in FDD Band 13 (currently used by Verizon Wireless in the U.S) two 10Mhz bands 777-787 Mhz and 746-756 Mhz are allocated for uplink and downlink transmission, respectively, and the base station transmits in the downlink band and receives in the uplink band; the users are also in half-duplex mode and receive in the downlink band and transmit in the uplink band. The goal of a full-duplex (FD) system is, however, to use a single band and simultaneously have both downlink and uplink transmissions on this band.

Full-duplex. A full-duplex system can potentially double the spectral efficiency by allowing simultaneous transmission and reception in the same frequency band. Nonetheless, the self-interfering (SI) signal from the transmitter to the receiver of the same node would seriously limit a full-duplex system if it is left untreated. Recent works have shown good improvement in terms of SI suppression by developing novel approaches which have been tested in different experimental testbeds by using SDR (Software Defined Radio) platforms.

Interference cancellation may be categorized as active or passive. In *active* cancelation, the cancellation circuit or algorithm adaptively follows the system changes and automatically makes the necessary adjustment, while in *passive* cancellation, the system is usually tuned once and it may only be adjusted at a much longer time scale. Interference cancellation can be achieved in different stages. In *RF interference cancellation* the two or more RF (radio frequency) signals destructively collide and generate a low power signal usually referred to as a null. For example two transmit antennas can be made to generate nulls in different points in the surrounding environment by feeding them with the same RF signal and controlling their phase and attenuation. RF cancellation may also be enabled in waveguides or RF circuits by receiving replicas of signals using two receive antennas and combining the signals by precisely controlling the gain and phase of the received signals. Alternatively, the received signal can be treated by subtracting self interference from the received signal by using digital cancellation techniques or using off-the-shelf analog noise cancellation circuits. While in theory one can solely employ digital cancellation techniques, current Analog-to-Digital converters do not have a resolution to pass the intended received signal with a power that is much below the interference signal power. Hence, several practical full-duplex (FD) systems [12], [11], [13], [14] have been proposed that couple RF cancellation along with digital cancellation to achieve the desired level of SI suppression.

RF cancellation may include a combination of antenna cancellation and analog cancellation. In [12], antenna cancellation was achieved by placing two transmit antennas asymmetrically at ℓ and $\ell + \frac{\lambda}{2}$ distance from the receive antenna. This allows the transmit signals to add π out of phase and hence cancel each other. On the other hand, analog cancellation involves the generation of a π phase shift internally, coupled with the estimation and compensation of the SI channel [11], [13], [14]. This allows for π phase shifters with a better frequency response over a wide-band channel to be employed, in contrast to the strong dependence on frequency (λ) posed by the antenna cancellation in [12]. In another approach, MIDU [8] employs antenna cancellation with *symmetric* placement of antennas and passive phase shifters for SI cancellation. Symmetric antenna placement allows for easy realization of several null points, therefore scaling to MIMO.

While all prior work on enabling full-duplex communication have used a clean slate approach by using SDR platforms, in this work, we consider the design of a full-duplex system that can be retrofitted to current base stations and mobile devices. We present the design and implementation of an experimental full-duplex system using an LTE base station. The use of legacy systems allows for possible deployment of full-duplex technology with much lower cost to operators. More importantly, we seek a design approach that does not need a change to the current 3GPP standards and can work with legacy half-duplex clients. Even though our research is still in its early stages and applicable only to small cell sizes, we believe our design and experimental results serve to motivate further study on the use of full-duplex technology in existing mobile broadband systems.

III. Challenges

Several challenges arise in realizing our vision of enabling full-duplex with legacy LTE systems.

Techniques for SI Suppression: Since we require that the base station (BS) hardware does not change, we cannot leverage digital cancellation techniques for SI suppression and would be restricted to analog cancellation. This raises several questions fundamental to our goal:

- Is analog cancellation sufficient to realize full-duplex, since otherwise full-duplex would not even be possible?
- Even if analog cancellation is sufficient, what is the extent (in terms of data rate and range) to which it can enable full-duplex?
- Also, can one rely on simple passive cancellation methods or would one also require active cancellation methods, the latter potentially leading to higher complexity?

These are important questions that need to be answered in understanding the limitations of enabling full-duplex with legacy LTE systems. We intend to understand and address them through real-world measurements and experiments.

Integration with Legacy BS Equipment: While addressing the above challenge will help us narrow down the potential techniques for effective SI suppression, we still need to understand how to realize them in an efficient manner with existing legacy BS equipment and hardware. To begin with, the BS equipment would serve as a black-box and would provide access only to the RF port and hence the RF carrier signal. Further, let us consider a simple single-input single-output (SISO) system for exposition of the challenges.

- Enabling SI suppression techniques: A single antenna is used for both transmission and reception, while the transmit and receive paths are isolated internally only inside the BS. FD techniques on the other hand primarily require the transmit and receive paths to be separated in order to benefit from the path loss attenuation in SI cancellation.
- Translating half-duplex to full-duplex: Since the legacy system is designed to operate in a half-duplex mode, the downlink and uplink signals are already modulated to go on different spectral carriers and bandwidths (say in FDD systems). Hence, to enable full-duplex, one needs to bring both the downlink and uplink signals onto the same carrier frequency and bandwidth. Further, this has to be achieved outside of the BS equipment.
- Utilization of legacy frequency bands: Legacy systems are already provisioned with separate bandwidths (say 10 Mhz for FDD) for downlink and uplink. Hence, it would not make sense to enable full-duplex only in one direction. To efficiently utilize the existing bandwidth allocations, one would need to enable full-duplex on either of the 10 Mhz bands. However, each BS equipment is designed to handle and process only two 10 Mhz signals, one on downlink and one on uplink, at any given time. Enabling full-duplex would effectively require the BS equipment to handle four 10 Mhz signals at the same time, for which it was not designed.

Transparency to Half-duplex Clients: Finally, even if full-duplex can be realized on the BS side, its benefits cannot be realized without participation from the clients, who form the other end of the link. Further, clients are antenna constrained compared to the BS. Hence, one approach to leveraging full-duplex with half-duplex clients is to employ two half-duplex clients for a full-duplex session, with one client serving as a transmitter to the BS, while the other one serving as a receiver to the BS [8]. However, this is still not sufficient, since the clients are designed to operate on specific separate bandwidths for their downlink and uplink signals, which in turn will prevent two clients from serving on uplink and downlink at the same time on the same bandwidth. The key challenge here is how to enable full-duplex in a transparent manner with half-duplex legacy clients without modifications to the standard.

IV. Design

Our design focus is on the use of passive interference cancellation in which the self interference signal is destructively combined at the receiver. Two main reasons drive our design approach: (i) It is not possible to change or modify legacy base stations. Therefore, it is not possible to use techniques such as digital interference cancellation or wideband cancellation [15]; (ii) It is very hard to tune the cancellation circuit by using automatic tunable phase shifters and attenuators. Hence, by sacrificing some performance we only consider cancellation circuits with manually adjustable components that are tuned once based on the position of the circuit elements and antennas. We consider different cancellation methods (evaluated experimentally in Section VI) including (i) Antenna cancellation by symmetric antenna placement; (ii) Using RF absorbers with limited view between the transmit and receive antennas of the same node in order to block direct line of sight between the transmit and receive antennas at the same node (and at the same time only minimally affect the multi-path components of the signal between this node and another node); (iii) Using polarized antennas to further separate the downlink and uplink signals into two different polarizations; (iv) Using directional antennas in order to provide better isolation and SI cancellation.

Since the amount of self-interference cancellation achieved though combination of the above approach is limited, we consider a confined deployment scenario in which the users are about 10 to 20 meters away from the base stations. This is obviously a first step in realizing full-duplex communication with legacy base stations. In order to enable such communication at longer distances, we would need more isolation. One possibility is to enable wideband cancellation techniques such as one proposed in [15] in a C-RAN (Cloud- Radio Access Network) type structure where the RRH (radio remote head) that encapsulates the transmit and receive chain is separated from the base station processing unit. Such change, does not require a change to the standards; however, it would need the addition of a processing element between the RRH and the C-RAN infrastructure.

A. How to realize full-duplex in commercial systems without modifying Base stations, User equipments, and standards?

A legacy base station works in half-duplex mode; there are two different frequency bands in FDD LTE for uplink and downlink. In order to use such a base station in the full-duplex mode it is necessary to bring both uplink (UL) and downlink (DL) bands to a single band. In particular we work with an LTE base station that implements Release 9 of the LTE standards and uses band 13 which spans 10 Mhz (777 to 787 Mhz) in the uplink and 10 Mhz (746 to 756 Mhz) in the downlink. We use frequency converters to convert these signals (as described below) to transmit over-the-air signals on two 10 Mhz bands centered at 2610 Mhz and 2590 Mhz for which we have experimental license.

We have designed and used a frequency converter using a combination of mixer, filter, and frequency synthesizer that

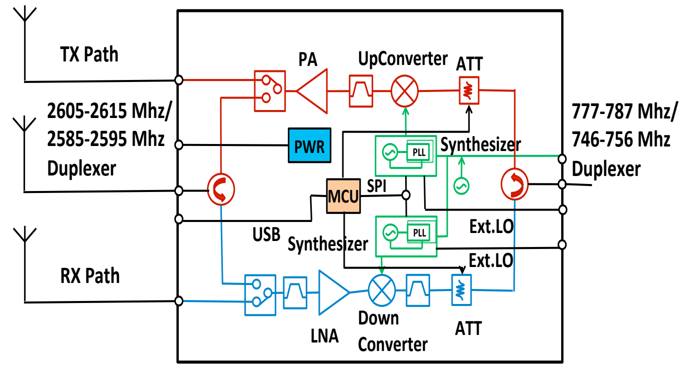


Fig. 1 Frequency Converter Circuit

can convert either of the frequency bands 777-787 Mhz or 746-756 Mhz to either of 2585-2595 Mhz or 2605-2615 Mhz bands. The conversion frequency is controlled by frequency synthesizers (could be an external frequency synthesizer such as Agilent MXG vector signal generator that we have used in our experiments), which could be set such that UL and DL happen in the same band.

In order to benefit from path loss attenuation in SI cancellation and enable FD operation it is also necessary to separate the transmit and receive paths. However, in existing BSs a single antenna is used for both transmission and reception while the signals are separated internally. We use a combination of circulators, isolators, and bandpass filter to separate the transmit and receive paths and bring both signals into the same band. Therefore a single antenna connected to one end of the frequency converter box would have two separate connections on the other end (Figure 1), one to transmit the signal and one to receive the signal, both in the same band. At this stage, we need to provide enough interference cancellation over the air to bring down the SI as much as possible. Although the desired SI cancellation is to reach the noise floor at the receive path, it is enough to lower it to a range between 5 to 30 dB lower than the received signal from the other node in order to be able to decode the packets from QPSK up to 64-QAM modulations with various channel coding rates envisioned in the standards. Note that a similar frequency converter will be used on both sides, one in the BS which maps the transmission band 746-756 Mhz and the reception band 777-787 Mhz to 2605-2615 Mhz and another frequency converter at the user equipment (UE) side that maps the transmission band 777-787 Mhz and the reception band 746-756 Mhz to the same frequency band 2605-2615 Mhz. Either of the transmit or receive antenna ports of the frequency converter can be connected to an antenna cancellation circuit in order to exploit single-level or two-level antenna cancellation [8].

In a C-RAN deployment it is possible to directly combine the functions of the frequency converters into a new design of the RRH. The connection between the BBU (baseband unit) and RRH is usually provided through analog or digital signal transmission that separates the uplink and downlink signals. Hence, it is possible to modify the RRH to have separate antenna ports by designing separate transmit and receive RF chains in the same frequency bands. If multiple bands are available, an LTE base station would be capable of frequency aggregation as provisioned in the standards.

B. How to keep the design of full-duplex in commercial systems transparent to HD clients?

Beside solving the problem of self-interference cancellation at the legacy base stations, we face the issue of providing the full-duplex gain using legacy clients. Our approach discussed in the prior subsection provides a solution that requires the clients to be externally modified and also use antenna cancellation at the clients. The performance of antenna cancellation at the clients might be limited due to their mobility and size constraints. It is, however, possible to modify the system to use full-duplex transmission/reception at the base station but half-duplex access at the clients. Let us consider the case that two bands A and B are available as depicted in Figure 4(i)(for example 2585-2595 Mhz for band A and 2605-2615 for band B). A set of legacy clients are designed to use band A for uplink and band B for downlink. With slight modification (that could be only a modem firmware update in the user equipment) we could have another set of clients that use band B for uplink and band A for downlink as illustrated Figure 4(i) . Note that no changes to the standard are required for enabling this scenario. By employing a pair of base stations that are full-duplex, one in band A and the other in band B and sharing their processing units, it is possible to serve both sets of users simultaneously in the two available frequency bands A and B. This potentially doubles the number of clients that a single legacy base station in half-duplex mode that uses band A for uplink and band B for downlink can serve, and it is not hard to see that a full-duplex system with both full-duplex base stations and full-duplex clients in the entire band A plus B would not provide any additional benefit over this system with full-duplex base stations and half-duplex clients.

We note in a system with duplex basestation, there will be new interference patterns that could prohibit maximal full-duplex gains, particularly due to the interference caused by the uplink clients to the adjacent dowlink clients that are served in the same frequency band. The problem of interference caused by uplink users on the downlink clients exists in any single cell full-duplex system including the system with full duplex clients or half duplex clients and it has been addressed in recent works [9], [10].

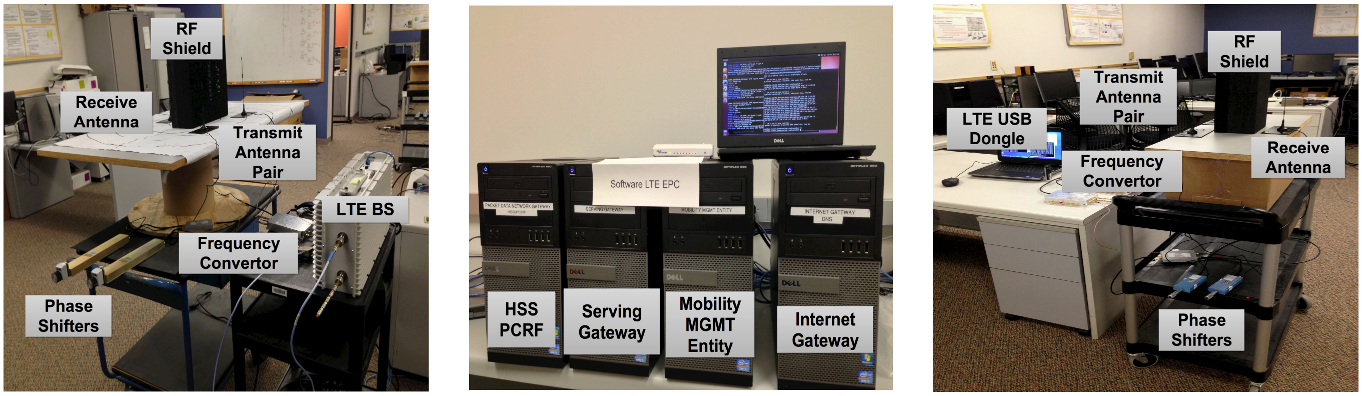
If multiple bands are available, two different approaches may be used with their own pros and cons. In first approach as discussed in Section IV-A a single full-duplex base station may be used by considering the fact that an LTE base station can use frequency aggregation as it is provisioned in the standard to serve over the aggregated band (not more than 20 Mhz aggregate). However, clients need to be modified by using frequency converters and boosted by antenna design and RF self interference cancellation circuits. In another approach it is possible to employ two separate base stations in conjugate uplink-downlink pair of bands as discussed in Section IV-B. This way clients need very minimal changes, and base station processing would also need only minimal change if it is centrally performed as in a C-RAN type deployment. Interestingly a C-RAN deployment of the system would benefit from central processing of both BBU and requires only a simple modification of the RRH units (to incorporate the function of the frequency converters) and the corresponding antenna design. Hence, the latter system would require the least change on both base station and UE sides. We were not able to test this scenario because we did not have access to a base station with separate BBU and RRH.

V. Experimental Setup

Our testbed consists of three parts: (i) a base station that is enabled to work in full-duplex by separating the transmit and receive paths, bringing the frequency bands in the uplink and downlink to the same band with the help of frequency converter circuits, and applying appropriate SI cancellation techniques; (ii) an evolved packet core (EPC) implementation that drives the base station and establishes and controls the connections with the clients as well as the Internet; (iii) a user equipment device which is a Band 13 USB dongle.

Base station and full-duplex enabler circuits: We use an NEC LTE, 3GPP Release 9 compliant small cell prototype base station (Figure 2(a)) which operates in the 700Mhz band (Band-13). The base station is equipped with two antenna ports for MIMO operation. In this work our focus is on the possibility of enabling full-duplex operation with legacy base station, hence, we have blocked one of the antenna ports by using large attenuators and a terminator. The other antenna port is connected to the designed frequency converter box in which the signal goes through a circulator to separate the transmit and receive paths, and then each path goes through a frequency conversion by using a mixer and proper bandpass filter. The transmit antenna port of the frequency converter box is then connected to antenna cancellation circuits. The receive antenna port is connected to an antenna. Due to the proximity of the antennas (about 30cm) the transmit and receive antennas are also separated by an RF absorber to further block the line of sight components of the signal as well as blocking a possible antenna coupling effect. The transmit antenna cancellation circuit is tuned once before the experiment and remained untouched throughout.

EPC: Since the base station is 3GPP LTE standards compliant, it had to be integrated with an LTE Evolved Packet Core (EPC) network for complete functionality. Our setup consists of the openEPC [3] platform which provides EPC functionality. The various components of openEPC are implemented using C that can execute either directly on Linux machines or a visualization setup like VMware. In our setup, we run openEPC components over four Intel-based servers such that certain components share the same machine as shown in Figure 2(b). This limited resource provisioning is sufficient since we run only a small number of flows in our experiments. The EPC network [1] consists of various components to ensure Internet connectivity for the LTE clients in addition to various management functionalities for the mobile



b) FD LTE base station | a) LTE EPC network | c) FD LTE client

Fig. 2 Full-duplex LTE testbed.

operators. The control plane functionality in the EPC network is provided by the MME (Mobility Management Entity), HSS (Home Subscriber Server) and the PCRF (Policy and charging rules function). The MME is in charge of session and subscriber management including user authentication, mobility management and idle terminal location management. The HSS includes a database that stores the user profile information while the PCRF manages the service policy and configures the QoS parameters for each user traffic flow. The data plane functionality in the EPC is split between the S-GW (Serving gateway) and the PDN-GW (Packet Data Network gateway). The S-GW acts as a local mobility anchor for user sessions as clients move across base stations. The PDN-GW is connected to multiple S-GWs and routes user traffic towards the external network. In addition to routing, the PDN-GW ensures policy enforcements for resource management and includes packet filtering and charging functions. The Internet gateway provides connectivity to the Internet and includes key functions like NAT, DNS and DHCP.

Client/User equipment: The client devices in our setup are Pantech USB dongles [4] that operate on Band 13 (Figure 2(c)). We use USIM cards obtained from Sysmocom [6] programmed with the appropriate identification name and secret code to ensure connectivity with the LTE network testbed. The antenna port of the client is connected to a frequency converter box similar to that of the one at the base station to isolate the transmit and receive signal paths as well as convert the frequency bands of the uplink and downlink transmissions to a single band. The only difference is that the frequency synthesizers used in the transmit and receive paths in the UE frequency converter side are swapped compared to those used on the base station side. Once again, the transmit antenna port of the frequency converter box is connected to a transmit antenna cancellation circuit and the transmit antennas and receive antennas are further isolated using RF absorber.

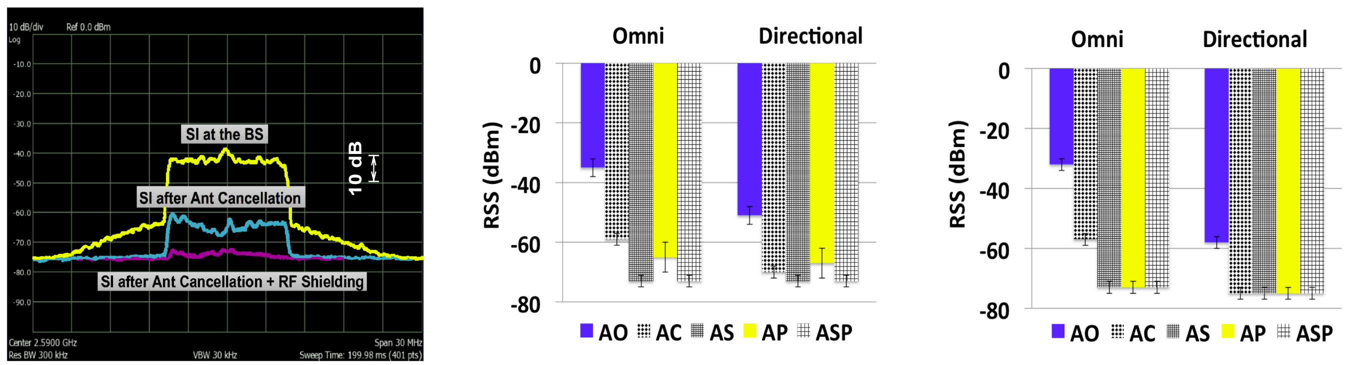
VI. Evaluation

In this section, we experimentally characterize the performance of our *FD-LTE* system. We first present an experimental evaluation of different passive SI suppression mechanisms over wideband LTE signals. Next, we compare the performance of *FD-LTE* to *HD-LTE* (half-duplex or legacy LTE) in an indoor environment.

A. Passive Self-Interference Suppression

Passive SI suppression, suppresses the direct Line of Sight (LoS) paths between the transmit and receive antennas, without relying on frequent self interference channel estimation. In this section, we evaluate the SI suppression capability of the following passive suppression mechanisms: (i) *Antenna cancellation:* our antenna cancellation approach is based on symmetric antenna placement [8]. Here an additional TX antenna is placed such that the RX antenna is at the same distance from the two TX antennas. Next the signal transmitted from one of the TX antennas is phase shifted using a fixed π phase shifter after passing through a splitter to help nullify the SI signal; (ii) *RF shielding:* we realize RF shielding by placing a slab of broadband foam microwave absorber between the RX and TX antennas. We used the C-RAM LF-75 [5] RF absorber in our experiments. LF-75 is a lightweight, flexible, and broadband RF absorber which is optimized for frequencies above 2.5 GHz. It is designed to provide typically 20 dB of reflectivity reduction and can be easily cut to fit the desired application; (iii) *Polarization:* we used L-Com RE05U antennas [2] for omnidirectional transmission and reception. This is a 5 dBi omnidirectional antenna with vertical polarization. We create orthogonal RX polarization by placing the RX antenna horizontally; (iv) *Directionality:* we used L-Com HG2614 patch antennas for directional transmission while maintaining the omnidirectional receive antenna. We place the receive antenna at the side lobe of the directional TX antenna(s) in order suppress the SI signal.

Setup. We measured the SI signal power corresponding to different passive SI suppression mechanisms in both indoor (multi-path rich) and outdoor (low multi-path) environments. We first deploy omnidirectional TX and RX antennas. TX antennas transmit 10 MHz LTE signals in the 2.59 GHz band. RX antenna is connected to a splitter in which one of the two ports is connected to an Agilent spectrum analyzer. We tune the spectrum analyzer to 2.59 GHz band in order to obtain the SI RSS value at the BS. We next measure SI RSS due to (i) antenna separation (30 cm distance between TX and RX



a) SI cancellation at the BS b) Indoor SI cancellation evaluation c) Outdoor SI cancellation evaluation

Fig. 3 Screenshot of SI suppression depicted by spectrum analyzer (a), and evaluation of different SI cancellation techniques (b, c): antenna separation only (AO), antenna cancellation (AC), antenna cancellation with RF shielding (AS), antenna cancellation with polarization (AP), antenna cancellation with RF shielding and polarization (ASP).

antennas), (ii) antenna cancellation, (iii) antenna cancellation + RF shielding, (iv) antenna cancellation + polarization, and (v) antenna cancellation + RF shielding + polarization. We next repeat the experiments after replacing omnidirectional TX antennas with directional patch antennas. We perform these experiments at five different randomly selected indoor and outdoor locations.

SI suppression evaluation. Figure 3(a) shows a screenshot of SI RSS as depicted by the spectrum analyzer. Here SI power prior to any cancellation is -42 dBm, which is reduced to -64 dBm after antenna cancellation, and to -73 dBm by adding RF shielding on top of antenna cancellation. Note that the noise floor value reported by Agilent is -75 dBm over a 30 MHz measurement bandwidth. Thus in the above sample, antenna cancellation + RF shielding reduces the SI signal to a value close to the noise floor.

Figures 3(b) and (c) depict the average effect of various SI cancellation techniques (denoted by AO: antenna separation only, AC: antenna cancellation, AS: antenna cancellation + RF shielding, AP: antenna cancellation + polarization, ASP: antenna cancellation + RF shielding + polarization) using omni or directional antennas in indoor and outdoor environments, respectively. It is seen that in both indoor (Figure 3(b)) and outdoor (Figure 3(c)) environments, antenna cancellation alone provides about 20-25 dB cancellation. This amount of cancellation provides close to maximum SI suppression with directional TX antennas. Note that since RX antenna can be placed at the side lobe of a directional TX antenna, there is already 16/26 dB (indoor/outdoor) reduction in SI just by employing directional TX antennas. Figures 3(b) and (c) show that additional cancellation mechanisms on top of directional TX antenna cancellation only slightly enhance the performance.

On the other hand, RF shielding boosts the cancellation by up to 14 dB when omni-directional TX antennas are employed. Figures 3(b) and (c) show antenna cancellation plus RF shielding provides close to maximum SI cancellation with omnidirectional TX antennas. Placing RX antenna horizontally (polarization), provides an average of 10 dB additional SI cancellation on top of antenna cancellation, which is slightly less than SI reduction due to RF shielding. Antenna polarization generally provides additional isolation in conjunction with antenna cancellation, however, our results do not show more SI cancellation by using polarization when the combination of antenna cancellation and shielding is already used.

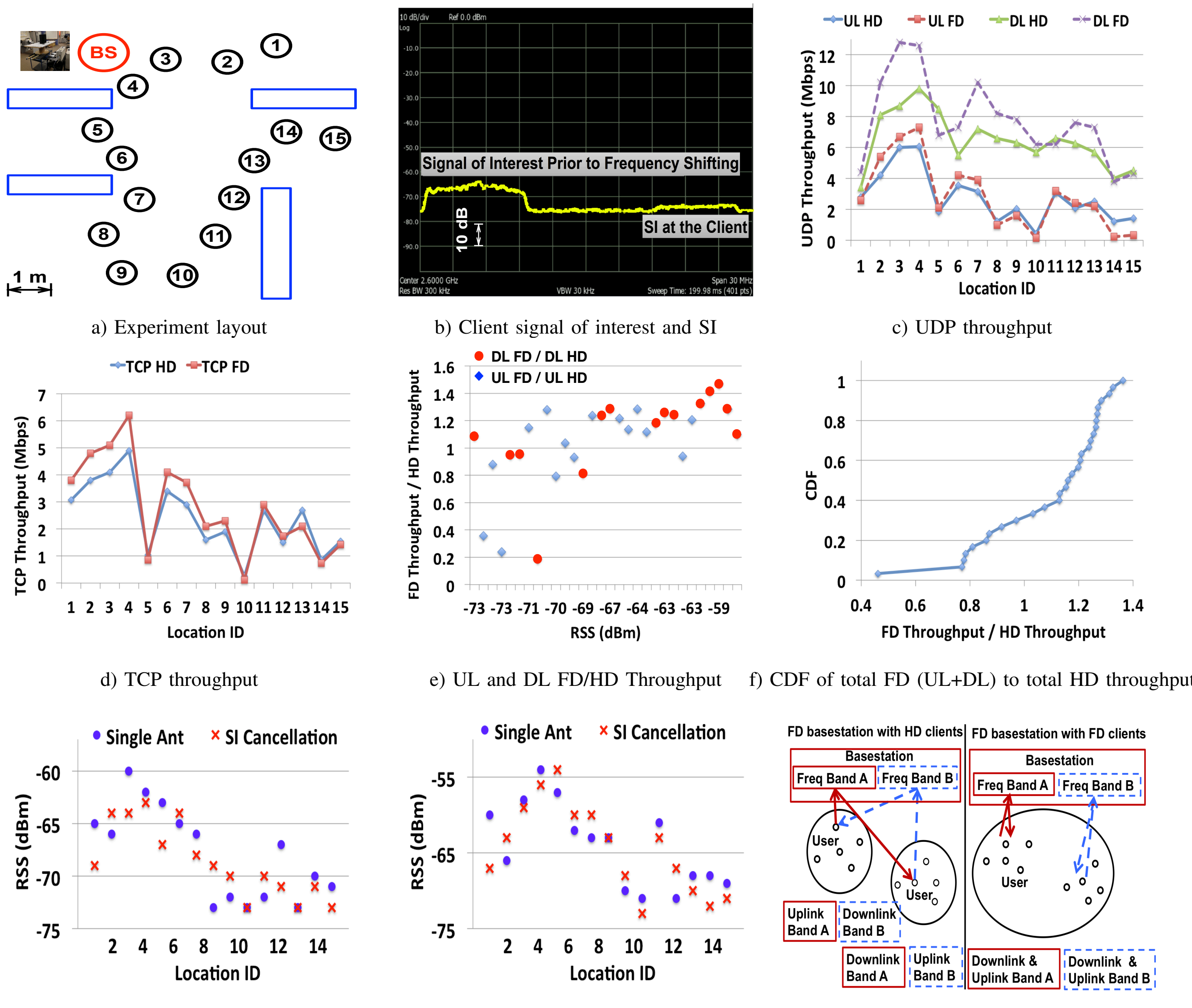
B. *FD-LTE vs. HD-LTE*

In this section we compare the performance of *FD-LTE* to *HD-LTE*. We use the second model in Figure 4(i) with full duplex clients and report the results based on that.

Setup. Figure 4(a) depicts our experiment setup in which we create an LTE network in an indoor office environment. Our LTE base station is located at a fixed location, whereas the client device location is varied to generate 15 different base station to client link conditions. We construct FD base station and client devices by employing frequency converters to put DL and UL on the same band (Section IV), and antenna cancellation + RF shielding (AS scheme) for SI cancellation. Note that our results in Section VI-A confirm that AS scheme provides maximum SI cancellation gain. We connect an Agilent MXG signal generator to the TX local oscillator port of the BS frequency converter. The same signal generator is connected to the RX local oscillator port of the client frequency converter. The signal generator simultaneously controls the BS downlink and client's receive frequency of operation and can shift the DL band to UL band to enable FD in *FD-LTE*.

In an example client location, Figure 4(b) shows the received signal as observed by the client in the entire DL band (2585-2595 Mhz) before it is moved to the UL band (2605-2615 Mhz), in comparison to SI signal already existing in this band, i.e., 2605-2615 Mhz. It is seen that the received signal energy is about 10 dB above the SI and this allows for reliable decoding in *FD-LTE*.

For each client location we take the following measurements. We first simultaneously run saturated UL and DL iPerf UDP sessions for a duration of 1 minute and store the corresponding throughput values. Next, we run a 1 minute UL



a) Experiment layout b) Client signal of interest and SI c) UDP throughput

d) TCP throughput e) UL and DL FD/HD Throughput f) CDF of total FD (UL+DL) to total HD throughput

g) SI cancellation impact on UL SNR h) SI cancellation impact on DL SNR i) System with HD clients vs. FD clients

Fig. 4 Evaluation of *FD-LTE* system and comparison with *HD-LTE*.

TCP session with TCP window size of 64KByte and store the resulting throughput values. The iPerf server is located in our core network to avoid the impact of backbone congestion on our results. For each client location, we also measure the BS DL RSS observed by the client by passing a copy of received signal to the spectrum analyzer using a splitter at the receiver. We take the same approach to measure the client's UL RSS as observed by the BS. We perform each experiment for 5 times and report the average value.

Next, we repeat the same throughput measurements by considering HD BS and client devices. Note that the *FD-LTE* system uses 10 MHz of total bandwidth for UL and DL operation. Thus in order to have a fair comparison, we configure the BS to use different 5 MHz bands for UL and DL in HD mode, such that the overall bandwidth remains the same. Further, we use a single fixed TX antenna for HD operation (*i.e.,* we remove antenna cancellation with RF shielding which is present in FD for SI cancellation).

Throughput comparison. Figures 4(c) and (d) depict the iPerf UL and DL UDP and UL TCP throughput values for both *FD-LTE* and *HD-LTE* systems. From Figure 4(c) we observe that in FD mode, DL stream almost always outperforms HD DL results and provides significant gains, while UL FD and HD have close to similar performances. We also observe that DL stream always achieves a higher throughput than UL stream irrespective of FD/HD operation mode. Similarly, Figure 4(d) shows that FD TCP throughput outperforms HD TCP throughput for over 60% of locations with an average throughput gain of 23 %.

In order to better understand the regions over which FD gains over HD, and the resulting aggregate gains, we plot the following: (1) $\frac{\mathbf{THR}_{DL,FD}}{\mathbf{THR}_{DL,HD}}$ and $\frac{\mathbf{THR}_{UL,FD}}{\mathbf{THR}_{UL,HD}}$ throughput ratios as a function of DL SNR and UL SNR, respectively, and (2) cdf of total FD (UL + DL) / total HD (UL + DL) throughput values across all 15 client locations for both UDP and TCP traffic patterns. Two key observations are made:

From Figure 4(e) we observe that in order to achieve gains in FD mode, received signal strength should be higher than -68 dBm. Since our observed SI at the client is typically around -73 dBm, this shows that the received signal strength should be at least 5 dB higher than SI in order to gain over HD mode. As the client moves closer to the BS, FD gains increase.

From Figure 4(f) we observe that in 65% of the client locations FD gains over HD system, and for 40% of the locations the gains are between 20-40%. Figures 4(c)-(f) show that our *FD-LTE* system can provide considerable gains over *HD LTE* with small cell sizes. As RSS decreases ($e.g.$, with increasing cell sizes), SI becomes comparable to RSS and cannot be ignored. In such cases in order to fully realize the benefits associated with FD, SI should be canceled through active cancellation schemes such as active digital cancellation.

Impact of SI cancellation on far-field users. It is important to quantify how much the SI cancellation technique affects the desired signal received from other nodes or transmitted to other nodes in the system beside the same node itself. Figures 4(g) and (h) show the received UL and DL signal strength corresponding to different client locations, when a single antenna is used in comparison to the case that SI cancellation is employed. Figures 4(g) and (h) show that the received signal energy is almost the same in both cases for both UL and DL directions in almost all location with a variance of a few dB that could be as a result of fading and not performing the measurement simultaneously. This shows that there is no corresponding increase/decrease in RSS due to the SI cancellation scheme employed, as one would expect from far-field fading.

VII. Discussions

Our full-duplex experiments with LTE were conducted in an indoor enterprise environment with a (client) range of 10-20 m with respect to the BS. Further, our LTE BS is a small cell prototype BS, whose transmit power is much smaller compared to that of commercial macrocell BSs. We note that passive analog cancellation approaches considered in this work will have their limitations in terms of the range over which they can support full-duplex. Hence, for typical macrocell ranges, it might be very hard to realize full-duplex without incorporating additional active and digital cancelation approaches, requiring modifications to legacy base stations. However, for targeted application scenarios like femto cells type small cells in enterprises, hotspots, etc., whose cell ranges are much smaller (few tens of meters), we believe that our approach to realizing full-duplex with legacy LTE base stations has much potential.

Our current realization of *FD-LTE* enables a BS to transmit and receive a single stream of data in each direction in a full-duplex manner. In [8] we showed that symmetric antenna placement (also employed in *FD-LTE*) easily extends to MIMO systems and demonstrated its feasibility with software defined radios and over 625 KHz narrowband signals. As part of our on-going research, we are extending *FD-LTE*'s design to enable MIMO + FD operation over wideband LTE signals.

VIII. Conclusions

In this paper, we presented the design and implementation of *FD-LTE*, an end-end experimental LTE system with full-duplex capability. *FD-LTE* incorporated and realized a combination of passive analog cancellation schemes for self-interference suppression, with legacy LTE half-duplex BS and client devices in a transparent manner. We built a prototype of *FD-LTE*, integrated it with LTE's evolved packet core network and conducted an extensive set of over-the-air experiments to explore the feasibility and potential for full-duplex in legacy LTE system. Promising results from our test-bed revealed that appropriate combination of passive analog SI suppression mechanisms can provide large amounts of self-interference suppression in both indoor and outdoor environments. We also showed that *FD-LTE* can provide gains of 20-40% compared to *HD-LTE* with a client range of 10-20 m with respect to the BS, that is typical of small cells specifically femto cells.

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