Millimeter Wave Mobile Network with Full-Duplex Mode

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Abstract. To converge full-duplex and mm-wave is attractive to high spectral efficiency and huge capacity in 5G mobile networks. However, this conjunction will bring more difficulties to design mobile networks. Except for the previous problems of inter-site interference and UE-UE interference, new challenge of ultra-broadband self-interference cancellation about wider bandwidth of mm-wave band occurs. In this paper, we propose a hierarchical mobile network of FDD/TDD massive MIMO and full-duplex mm-wave communications, which has the features of beam division multiple access and filtered sub-band reuse against inter-site interference and UE-UE interference. In addition, we also give a feasible analysis and system consideration of ultra-broadband self-interference cancellation based on microwave photonics and integrated polarization based antenna.

Keywords: Full-duplex · 5G · mm-wave mobile communication
Beam division multiple access · Self-interference cancellation
CU split · Microwave photonics

1 Introduction

In communication research, 5G is now one of the most popular events. There are several initiatives proposed for 5G, in which spectral efficiency is one of the most important ones. To improve the spectral efficiency by full-duplex (FD), in which transmission and reception can occur simultaneously in the same frequency band, is one of the most promising techniques. In our previous presentation, we investigated the challenges and potential application scenarios of FD in future 5G network [1]. For macrocell (with 47 dBm of average output power), 147 dB self-interference cancellation (SIC), and about 87 dB dynamic range of receiver are needed, which are great challenges for algorithm and receiver frontend. For smallcell (with 27 dBm of average output power), 127 dB self-interference cancellation, and about 67 dB dynamic range of receiver are needed, which are somewhat less than macrocell. Furthermore, for FD cellular network, inter-site interference and UE-UE interference are big issues. Simulations show 36 dB and 23 dB UL SINR degradation for macro and small cell respectively due to inter-site and UE-UE interferences. As for massive MIMO, large scale analog and digital cancellation matrix will bring much complexity. So our

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previous studies conclude that FD could be applied in the scenarios of single TX output power <27 dBm, the numbers of antenna less than 8, new spectrum and new air interface. This implies that possible application scenarios of FD would be smallcell, new introduced mm-wave band, and wireless fronthaul and backhaul.

The mm-wave frequency bands (defined as frequency band in 6–100 GHz) have much more available bandwidth than the legacy bands in the sub-6 GHz used today. They can therefore support the much higher data rates that are required in future mobile broadband access and backhaul networks. Although the conjunction of FD and mm-wave is more attractive to improving spectral efficiency and data capacity of 5G mobile networks, FD mm-wave communications would bring new challenges. The feature of wider bandwidth of mm-wave band results in more difficulties in designing FD SIC transceivers, especially analog front end (AFE).

In this paper, to deal with the problems of inter-site interference and UE-UE interference, we propose a hierarchical mobile network of FDD/TDD massive MIMO and FD mm-wave communication, which has the features of beam division multiple access (BDMA) and filtered sub-band reuse (FSR). In addition, we also introduce and discuss microwave photonics based SIC and integrated polarization based SIC antenna suitable to ultra-broadband FD mm-wave AFE.

2 Architecture of FD mm-wave Mobile Network

2.1 CU Split and Hierarchical FD mm-wave Mobile Network

As mentioned above, FD is suitable for using in new frequency band and new air interface. Therefore, new introduced mm-wave band can be considered as a FD frequency band in the future 5G because backward compatibility is not required. In order to ensure the robustness of control signaling, we consider the split of control plane and user plane of hierarchical FD mm-wave mobile network. Macro coverage by FDD/TDD massive MIMO below 6 GHz band mainly carries signaling, some data services such as broadcasting services (mobile CDN), as well as data services in the areas of coverage hole of mm-wave. 28 GHz or 38 GHz mm-wave band builds mm-wave smallcell. Figure 1 shows the hierarchical network of FDD/TDD massive MIMO and FD mm-wave networks, in which the C-plane and the U-plane are decoupled from each other by ensuring that the C-plane signaling seamlessly covers the whole networks. The high data rate is served by the mm-wave base stations. In the macro-coverage cells, radio resource control (RRC) manages signaling, traffic control and low data rate services.

At the same time, for a UE within a coverage area of the mm-wave base station, it keeps dual connections with mm-wave base stations and macro stations. The mm-wave base station is only responsible for the dynamic resource allocation of U-plane while the RRC connection and mobility control remain in the C-plane based on FDD/TDD macro station. In addition, macrocells and mm-wave cells are coordinated with each other through CloudRAN. The information such as the user's preferred content, moving speed and direction of the user beam is stored and held in the mobile edge computing (MEC) node, which front hauls all related services and information to the base station.

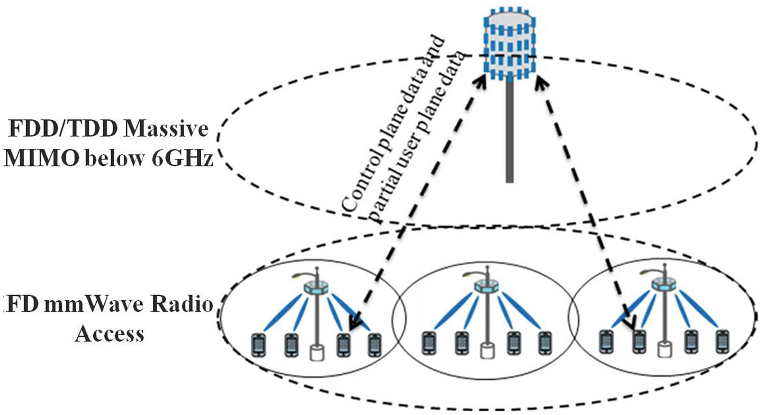

Fig. 1. Architecture of FD mm-wave mobile network.

2.2 Filtered Sub-band Reuse Between FD mm-wave Smallcell

For FD mobile networks, inter-cell interference is the biggest challenge. Although the narrow-beam characteristics of mm-wave reduces the interference of line of sight (LOS), interference of none line of sight (NLOS) caused by reflection becomes the main problem. Related research shows that in the worst case, due to the reflection caused by environments the background noise floors up about 46 dB. In order to solve the challenge of inter-cell interference of FD mm-wave networks, the mm-wave frequency band can be divided into several sub-bands of 300 MHz–500 MHz. Fortunately, there is about 1–3 GHz bandwidth of the candidate spectra of mm-wave bands in several main areas around the world [2]. Filtered sub-band reuse (FSR) is used throughout the FD mm-wave mobile network. Figure 2 is a typical 1×3 FSR or multiplexing. For example, the available mm-wave band of 28 GHz or 38 GHz is divided into three filtered sub-bands FS1, FS2 and FS3. Each cell is in a single sub-band FD, meanwhile, the self-interference cancellation of single sub-band full-duplex can be achieved through various cancellation technologies in Sect. 3.

For FSR, sub-band filter is added on top of OFDM, UFMC of FBMC, without any change on existing OFDM. Independent subcarrier spacing, CP length and TTI configuration could be for each sub-band. Rather low guard tone overhead between neighboring sub-band can be designed. FSR also supports asynchronous inter-band transmission due to perfect OOB performance.

Furthermore, dynamic FSR can be employed, i.e., different bandwidths are dynamically allocated to different cells according to traffic conditions.

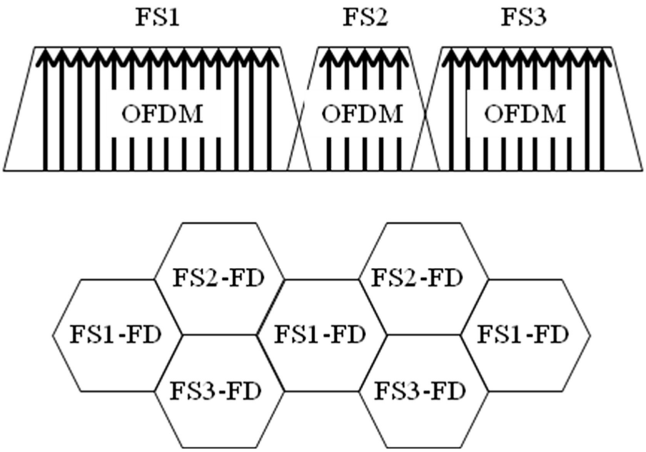

Fig. 2. Filtered sub-band reuse of FD mm-wave mobile network.

2.3 FD mm-wave Smallcell and BDMA

UE-UE interference is also a major challenge for FD mobile networks. To the interference of UE-UEs, beam division multiple access (BDMA) is introduced, as shown in Fig. 3, which can compress the interference of UE-UE in mm-wave FD scenario, on the other hand, achieve the virtual personal cell.

BDMA is the latest resource allocation technique in which orthogonal beams are allocated to each UE. Several beams of base station will be formed and point to different UEs to provide multiple accesses. If the UE and the base station are in LOS, they can transmit beams pointing to each other for proper communication without causing any interference to the other UE. The base station, after evaluating the position and the moving speed of the UE, assigns a separate beam to each UE. Based on the position and the moving speed, the base station also calculates the widths and the directions of the beams of all the UEs. Usually, all beams are different for each UE, so that different UEs can simultaneously transmit data at the same frequency with different angles.

Narrow and strong directional beam is the inherent property of mm-wave transmission. If coupled with beamforming, the mm-wave beam can be much narrower, which is more benefit to BDMA and FD transmission. Depending on various propagation environments, the base station can also more flexibly change the directions, numbers and beam-width of the beams.

For CU-separated and hierarchical FD mm-wave mobile networks, the UE will be a dual-connected terminal. The UE is assigned a signaling beam from FDD/TDD massive MIMO macro-cell as well as being assigned a mm-wave beam from FD smallcell.

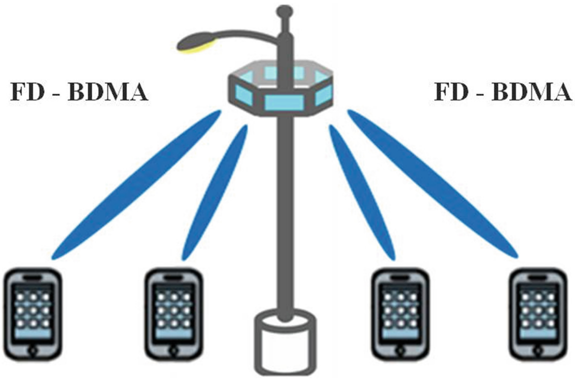

Fig. 3. BDMA of FD mm-wave smallcell.

3 Key Enabling Technologies: FD Ultra-Broadband Analog Frontend

3.1 Integrated Polarization-Based Antenna

Although, to a certain extent, the FD mm-wave mobile network architecture solves the interference of BS-BS and UE-UE, the ultra-broadband SIC, especially ultra-broadband analog SIC, is still the most critical technology, because to achieve ultra-broadband analog SIC is more difficult. At first, analog SIC can be performed at the antenna. Fortunately, an ultra-broadband polarization-based SIC antenna has been proposed and designed, as shown in Fig. 4 [3]. An auxiliary port AUX is introduced on the RX antenna that is co-polarized with TX and terminated with a reflective termination to achieve ultra broadband SIC.

The cross-polarized TX and RX antennas are used to improve the initial isolation between the TX output and the RX input. This increases the TX-to-RX isolation from 12–22 dB to 32–36 dB at 54–66 GHz. To improve TX-to-RX isolation and further suppression from ambient scattering, the SIC is aided by introducing a sub-antenna co-polarized with TX antenna. The sub-antenna is set on the AUX port on the RX antenna. The AUX port creates an indirect path from the TX output to the RX input. The indirect path indicates that the first cancellation signal is coupled to the AUX port and then reflects the reconfigurable terminal from the reflector chip and eventually couples to the RX input to cancel the self-interference from the direct path. The SIC bandwidth depends on how well the amplitude and phase match across the frequency band. A detailed algorithmic design technique for the SIC antenna is described in reference [3], in which 50 dB isolation over 300 MHz at 4.6 GHz is achieved. Reflective termination can be reconfigured to combat the variable self-interference scattering from the environment. Total self-interference suppression >70 dB over 1 GHz bandwidth at 59 GHz is demonstrated even in the presence of an environmental reflector [3]. RF canceller does not have any effect on RX noise floor due to antenna cancellation.

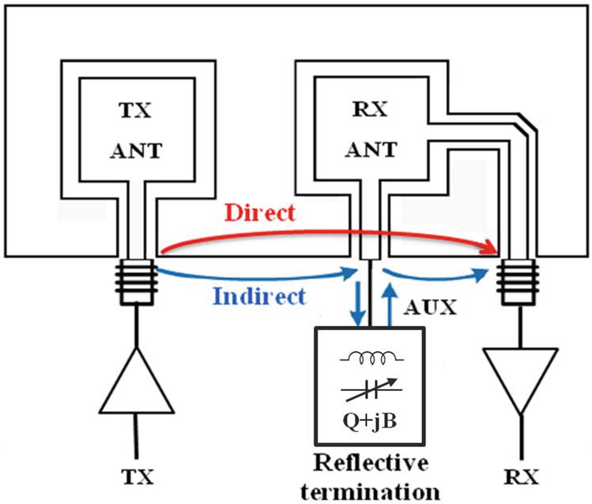

Fig. 4. FD integrated polarization based mm-wave antenna.

3.2 Ultra-Broadband RF Self-interference Cancellation Based on Microwave Photonics

For ultra-broadband analog SICs, the need for accurate amplitude and phase matching of large bandwidths places a heavy burden on the RF circuits, which are limited by the poor frequency flatness. In particular, RF delay lines and phase shifters are inherently narrowband and lack of the precision to achieve high performances of SIC. In the microwave photonics based SIC, simulated interference signals and received signals are all modulated onto the optical carriers and processed in the optical domain. In spite of exploiting the small portion of the bandwidth of the RF modulated optical signal, the microwave photonics based SIC can show an ultra-broadband cancellation.

In microwave photonics based ultra-broadband SIC system, each RF signal passes through an orthogonal bias M-Z modulator that modulates the RF signal onto an optical carrier. By high-precision channel matching, the amplitude and phase of the interference signals should be nearly the same in both receiver and cancellation paths, if subtracted by a balanced photodetector.

However, in the application scenario of mm-wave mobile network, the multipath and reflection of the beam must be considered in the ultra-broadband SIC. This is also the most critical factor to realize ultra-broadband SIC. Due to the antenna beamforming in the mm-wave system, the LOS interference is suppressed and the NLOS interference is amplified. In some environments, NLOS interference may be the primary interference. Because of the delay associated with the NLOS reflection, the interference canceller will need to adapt to larger dynamic delays. Therefore, multi-tap microwave photon FIR filter is a viable option. Considering the compactness and applicability, the photonic integrated circuits (PIC) is promising for the ultra-broadband SIC. Figure 5 is the ultra-broadband SIC system architecture based on PIC [4]. The PIC-based SIC replicates the transmitter interference as really as possible before subtracting the real interference from the received signal. To estimate the channel effect, the PIC based SIC uses a channel matched filter, which consists of N pairs of tunable weights and delays. Each pair may be used, for example, to represent different multipath effect in the transmitter-receiver path. In general, the channel matched filter is an optical FIR matched filter that attempts to simulate the channel response as really as possible and maximize self-interference cancellation. The received signal is carried by the top path in the Fig. 5 and represents a normal optical RF link. The simulated interference signal is tapped from the transmitter antenna and modulated onto the N different wavelengths in the bottom path of Fig. 5. The N wavelength signals propagate to a channel matched filter that assigns each wavelength to a separated tap. After each component is weighted and delayed by the semiconductor optical amplifier (SOA) and the true time delay (TTD), the wavelength signals are recombined. The resulting sum represents the estimated interference signal after the channel effect. The received signal and the estimated interference signal are then fed to the opposite port of the balanced photodetector to perform the subtraction. It should be noted that the balanced photodetector subtraction is suitable for both in-band and out-of-band interference, making it more efficient than simple filtering. Based on PIC, about 40 dB SIC over 1 GHz RF bandwidth has been demonstrated [4].

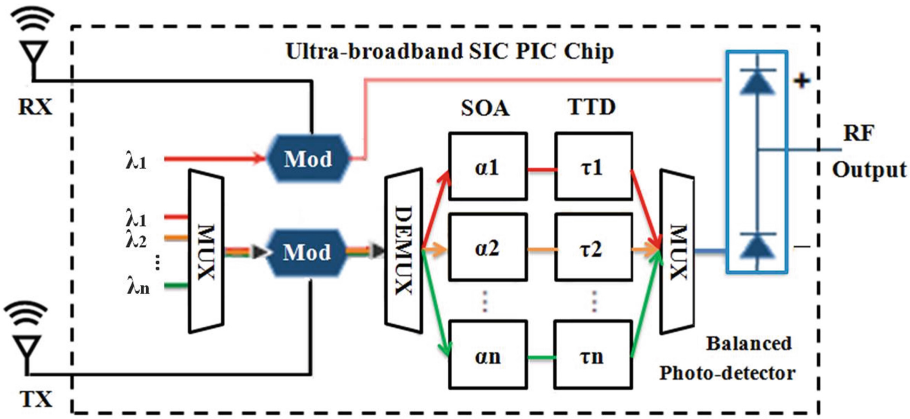

Fig. 5. FD mm-wave ultra-broadband SIC based on integrated microwave photonics.

4 Conclusion

In summary, to combine FD and mm-wave can boost the spectral efficiency and data capacity. A hierarchical network of FDD/TDD massive MIMO and FD mm-wave communications has the potential to realize FD mm-wave mobile networks, in which the features of CU split, BDMA and FSR make a true FD mobile network more feasible. On the other hand, PIC based ultra-broadband SIC and integrated polarization based antenna have respectively achieved self-interference suppression about 40 dB and 70 dB over 1 GHz bandwidth, opening a promising future of FD mm-wave mobile network of 5G.

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