FBMC Duplexing: Advantages and Problems

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***Abstract*—In this paper, we propose a FBMC (filter bank multicarrier) duplexing scheme, where downlink and uplink use FBMC for their transmission. Downlink and uplink transmit at the same time and in the same frequency band but with different subcarriers. We then analyze the advantages and problems of the scheme. We show that it is impossible to achieve full synchronization in time and frequency with both downlink and uplink signals. Thus the synchronization errors will destroy the orthogonality between the downlink and uplink. It is shown that the synchronization errors cause the OFDM (orthogonal frequency division multiplexing) duplexing to be unreliable, while FBMC duplexing with proper prototype filter is very robust to such errors. An additional advantage of FBMC duplexing is the reduced number of null subcarriers required to control the out-of-band emission. The distinguished advantages make FBMC duplexing a better choice in applications like small cell, spectrum sharing, spectrum refarming and cognitive radio. Some problems are pointed out, which include high peak to average power ratio (PAPR), large dynamic range, and requirement for high resolution analog to digital converter (ADC). Simulations at various situations are shown to verify the results.**

I. Introduction

Duplexing is a technology to allow two-way communication between two connected parties. Usually we call one of the way (direction) uplink and the reverse way (direction) downlink. Since uplink and downlink communication can happen at the same time, we need some mechanisms to separate the signals so that they will not interfere with each other. In general, we can separate the signals using different frequencies, or different time periods, or different codes. In other words, we can separate signals by making them orthogonal in a certain domain.

Time division duplexing (TDD) and frequency division duplexing (FDD) are the two most popular duplexing schemes. In TDD downlink and uplink signals use different time, while in FDD the two signals use different frequencies. Both TDD and FDD are widely adopted in various communication systems. The major problems of the two schemes are as follows. TDD needs stringent time synchronization and a guard interval to deal with the propagation delay. Downlink and uplink transmission occur at separate time periods that may affect some delay-critical applications. FDD needs frequency separation (guard band) to avoid interference. It usually needs a paired band with large separation. Other than TDD and FDD, full duplexing has also been studied extensively in recent years. Although full duplexing achieves the maximum capacity, the interference caused by the leakage of transmitting signal to the receiving signal is still a big problem. The time of full duplexing is still not coming yet. Please refer to [1, 2] and the references inside for more information.

Orthogonal frequency division multiplexing (OFDM) has been widely adopted in various communication standards. Recently OFDM has also been proposed for duplexing, where the downlink and uplink use different subcarriers of the same frequency band for their transmission [3–7]. In OFDM duplexing, the downlink and uplink signals do not interfere with each other as they are orthogonal. Orthogonality is the key for OFDM duplexing but this orthogonality may be destroyed by the non-ideal radio or by non-perfect synchronization. In fact, OFDM duplexing is very vulnerable to frequency offset and timing error.

In recent years, filter bank multicarrier (FBMC) has recaptured widespread interests for its possible applications in cognitive radio and dynamic spectrum access [8–10]. Like OFDM, FBMC is also a multicarrier scheme. Compared to OFDM, FBMC uses a much well localized prototype filter. The localization of the FBMC signal in both time and frequency makes it more robust to timing error and frequency offset. As such, we propose a FBMC duplexing scheme, where downlink and uplink use FBMC for their transmission. Downlink and uplink transmit at the same time and in the same frequency band but with different subcarriers.

We point out that FBMC duplexing has some distinguished advantages and also undeniable problems. It is shown that it is impossible to achieve full synchronization in time and frequency with both downlink and uplink signals. Thus the synchronization errors will destroy the orthogonality between the downlink and uplink. The synchronization errors cause OFDM duplexing to be unreliable, while FBMC duplexing with proper prototype filter is much more robust to such errors. An additional advantage of FBMC duplexing is the reduced number of null subcarriers to control the out-of-band emission. Based on the advantages, we show that it is ideal to use FBMC duplexing in systems such as small cell, spectrum sharing, spectrum refarming and cognitive radio, which are conjectured to be major technologies in 5G [10, 11]. We also point out some problems in FBMC duplexing including: high peak to average power ratio (PAPR), large dynamic range, and requirement for high resolution analog to digital converter (ADC). Finally we show simulations at various situations to verify the results.

II. FBMC duplexing

A. A brief review of FBMC

The design of a FBMC system is to select a few parameters including prototype filter $p(t)$, time duration T and subcarrier space F [8, 12–14]. Assume that we are going to transmit a data sequence using N subcarriers. The data sequence is

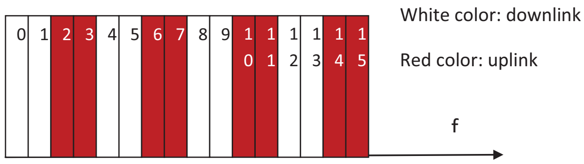

Fig. 1. An example for downlink and uplink subcarrier allocation

divided into blocks of length N and denoted by: $\bar{s}_n(k),\ k = -N/2, \cdots, N/2-1; n = 0, 1, \cdots, M-1$, where N is the number of subcarriers in the FBMC system. Thus NF is the whole bandwidth used for the system. The data sequence is then modified to $s_n(k) = \bar{s}_n(k)d_n(k)$, where $d_n(k)$ are modulation coefficients independent to the data. The modified data sequence is modulated to an analog signal expressed as

$$x(t) = \sum_{k=-N/2}^{N/2-1} \sum_{n=0}^{M-1} s_n(k)p(t-nT)e^{j2\pi kFt}. \tag{1}$$

The expressions here are very general and can be applied to different systems. In literature, there are some systems like FMT (Filtered Multiple Tones) and OFDM/OQAM (Offset Quadrature Amplitude Modulation). They are treated as special cases here using the expressions above. For general FBMC or FMT, $\bar{s}_n(k)$ can be any type of modulation (complex or real) and $d_n(k) = 1$. For OFDM/OQAM, $\bar{s}_n(k)$ must be real and $d_n(k) = j^{n+k}$, where $j = \sqrt{-1}$.

At the receiver, let $\bar{x}(t)$ be the received signal. The signal is matched with the prototype filter to obtain:

$$z_n(k) = c_p \int_{-\infty}^{\infty} \bar{x}(t)p(t-nT)e^{-j2\pi kFt}dt \tag{2}$$

where c_p is a positive constant to normalize the output.

Note that the prototype filter is generally chosen such that the signals at different subcarriers are approximately orthogonal. Thus usually a single tap equalization is used to recover $\bar{s}_n(k)$ from $z_n(k)$.

B. FBMC duplexing scheme

For FBMC duplexing, we only need a single band. Let W be the bandwidth. The band is divided into N subcarriers with subcarrier space being $F = W/N$. The subcarriers are divided into two subsets: Ω_D and Ω_U, where $\Omega_D \bigcup \Omega_U = \{0, 1, \cdots, N-1\}$. Ω_D is the subset of subcarriers for downlink, while Ω_U is the subset for uplink. Downlink and uplink use the same FBMC modulation. Downlink only transmits data at subcarriers in Ω_D and put zeros (nulls) on subcarriers in Ω_U, while uplink only transmits data at subcarriers in Ω_U and put zeros (nulls) on subcarriers in Ω_D. Within each subset, downlink/uplink can also choose to null some subcarriers to reduce interference or out-of-band emission. Figure 1 shows an example for subcarrier allocation for downlink and uplink when $N = 16$. In general, the allocation of subcarriers should consider factors like frequency diversity and mutual interference between downlink and uplink [7].

Let $s_{1,n}(k)$ and $s_{2,n}(k)$ be the data to be transmitted by downlink and uplink respectively. The downlink and uplink signals are denoted by $x_1(t)$ and $x_2(t)$ respectively, and can be written as

$$x_1(t) = \sum_{k\in\Omega_D} \sum_{n=0}^{M-1} s_{1,n}(k)p(t-nT)e^{j2\pi kFt}, \tag{3}$$

$$x_2(t) = \sum_{k\in\Omega_U} \sum_{n=0}^{M-1} s_{2,n}(k)p(t-nT)e^{j2\pi kFt}. \tag{4}$$

As Ω_D and Ω_U do not have intersection, the two signals are orthogonal: $\int_{-\infty}^{\infty} x_1(t)x_2^*(t)\mathrm{d}t = 0$. Thus the signals can be separated without interference at ideal conditions, even if the two signals are received at the same time.

Both FDD and FBMC duplexing use different frequencies for downlink and uplink, and allow downlink and uplink to occur at the same time. The difference is: FDD needs large frequency separation between downlink and uplink, while FBMC duplexing allows uplink and downlink signal to overlap, and does not need frequency separation as downlink and uplink are orthogonal. Like OFDM, FBMC is also a multi-carrier scheme. Thus it possesses the advantages of OFDM. Moreover, it is known that FBMC is more robust to synchronization errors [9, 13] and produces lower out-of-band emission than OFDM. Thus it is a better choice to use FBMC for duplexing.

Compared to other duplexing schemes, the major advantages of FBMC duplexing are as follows.

(1) It uses the same frequency band for downlink and uplink and does not need guard band or guard interval between downlink and uplink. FBMC duplexing allows uplink and downlink signals to overlap and does not need frequency separation as downlink and uplink are orthogonal.

(2) Compared to OFDM duplexing, FBMC duplexing is more robust to the leakage interference due to its better frequency localization.

(3) Compared to TDD, it is easier to control the cross interferences among base stations (BS). In TDD, BSs with the same frequency band may interfere with each other if one BS is receiving signal (the cell is in uplink mode) while another BS is transmitting signal (the cell is in downlink mode). To solve the problem, BSs are required to synchronize their downlink and uplink intervals, that is, they must do uplink and downlink at the same time. For FBMC duplexing, the cross-BS interferences can be avoided by assigning the same subbands for all BSs in downlink.

(4) OFDM duplexing needs stringent time and frequency synchronization between the uplink and downlink so that the uplink and downlink OFDM signals are orthogonal. For FBMC duplexing, synchronization for uplink and downlink is also important, but it is less vulnerable to synchronization errors. This will be discussed in the next section in detail.

(5) FBMC duplexing is more suitable for multi-cell spectrum sharing. If neighboring cells use the same frequency band but different subbands/subcarriers, time and frequency synchronizations are needed. FBMC is more robust to the

synchronization errors than OFDM duplexing, which means that it is more tolerable to inter-cell interferences.

(6) FBMC duplexing needs less null subcarriers to control the out-of-band emission than OFDM duplexing. When the same number of null subcarriers is used at the edges of the band for both FBMC and OFDM, the out-of-band interference in FBMC is much lower.

III. Synchronization errors in FBMC and OFDM duplexing

As we have mentioned above, both FBMC and OFDM duplexing rely on the orthogonality between the downlink and uplink signals. However, the orthogonality can be destroyed by a number of factors. One such factor is non-synchronization. In general it is very hard to fully synchronize the two signals at different locations. When there is only one signal, we can estimate the synchronization errors (timing and frequency errors) and then regain synchronization based on the estimated values. When there are multiple signals mixed together, even if we have the estimations of the synchronization errors, we cannot regain synchronization with all the signals. We can only choose to regain synchronization to one of them. Thus in general there always exist synchronization errors. In the following we explain this point in detail.

As an example, we consider a base station (BS) that transmits downlink signal $x_1(t)$ to terminals and receives uplink signal $x_2(t)$ from a terminal at the same time. To simplify the notations, we use $x_1(n)$ and $x_2(n)$ to denote the discrete (sampled) version of $x_1(t)$ and $x_2(t)$, respectively, that is, $x_1(n) = x_1(nT_s)$, $x_2(n) = x_2(nT_s)$, $T_s = \frac{1}{NF}$. Here the BS needs to decode the uplink signal $x_2(t)$, which is its desired signal, while the downlink signal $x_1(t)$ is the undesired signal (interference). Thus the overall discrete signal at the BS is

$$\begin{aligned} y(n) &= e^{j2\pi\epsilon_1 n}\alpha x_1(n-\tau_1) \\ &\quad + e^{j2\pi\epsilon_2 n}\sum_{l=0}^{L} h(l)x_2(n-l-\tau_2) \end{aligned} \tag{5}$$

where τ_1 and τ_2 are the relative time delays for the downlink and uplink signals, respectively, α is the channel gain for the downlink signal (here it is reasonable to assume a flat fading channel for the downlink signal as the propagation distance is very short), $h(l)$ is the channel for the uplink signal, and ϵ_1 and ϵ_2 are the carrier frequency offsets (CFO) of the downlink and uplink signals, respectively.

In conventional system using TDD or FDD, the interference $x_1(n)$ does not exist. Thus it is possible to estimate ϵ_2 and τ_2 and then regain synchronization. Now due to the mixing of the two signals, it will be very hard to estimate the CFOs and delays. Furthermore, even if we have accurate estimation of them, it is impossible to fully regain synchronization with both signals. In fact, if we compensate the overall signal by CFO ϵ and delay τ, the signal after compensation becomes

$$\begin{aligned} \hat{y}(n) &= e^{j2\pi\hat{\epsilon}_1 n}\alpha x_1(n-\hat{\tau}_1) \\ &\quad + e^{j2\pi\hat{\epsilon}_2 n}\sum_{l=0}^{L} h(l)x_2(n-l-\hat{\tau}_2) \end{aligned} \tag{6}$$

where $\hat{\tau}_1 = \tau_1 - \tau,\ \hat{\tau}_2 = \tau_2 - \tau$, are the final actual timing errors for the downlink signal and uplink signal, respectively, and $\hat{\epsilon}_1 = \epsilon_1 - \epsilon,\ \hat{\epsilon}_2 = \epsilon_2 - \epsilon$ are the final actual CFOs for the downlink signal and uplink signal, respectively.

In general, there do not exist any τ and ϵ such that $\hat{\tau}_1 = \hat{\tau}_2 = 0$, and $\hat{\epsilon}_1 = \hat{\epsilon}_2 = 0$. In fact, if so, we have $\tau_1 = \tau_2$, and $\epsilon_1 = \epsilon_2$. This happens with zero probability. That means it is impossible to find any estimation and compensation methods to eliminate the timing error and CFO completely. Thus the residue timing errors and CFOs will always cause the subcarriers to be non-orthogonal and induce inter-carrier interferences (ICI). Since the downlink signal has much higher power, the uplink signal may be severely interfered. Robustness to synchronization errors is thus the key to the reliability of the schemes.

The equalized signal at the BS is:

$$z_m(l) = c_p \int_{-\infty}^{\infty} \hat{y}(t)p(t-mT)e^{-j2\pi lFt}dt. \tag{7}$$

After some mathematical derivation, it can be expressed as

$$\begin{aligned} z_m(l) = c_p &\sum_{k\in\Omega_U,n} s_{2,n}(k)\int P(f-(k+\hat{\epsilon}_2 N)F) \\ &\cdot P^*(f-lF)H(f)e^{-j2\pi((n-m)T+\frac{\hat{\tau}_2 T}{\lambda N})f}\mathrm{d}f \\ &+\alpha c_p \sum_{k\in\Omega_D,n} s_{1,n}(k)\int P(f-(k+\hat{\epsilon}_1 N)F) \\ &\cdot P^*(f-lF)e^{-j2\pi((n-m)T+\frac{\hat{\tau}_1 T}{\lambda N})f}\mathrm{d}f \end{aligned} \tag{8}$$

where $P(f)$ and $H(f)$ are the Fourier transform of $p(t)$ and $h(t)$ respectively, and P^* means the conjugate of P.

From this expression we see that: (1) $z_m(l)$ ($l \in \Omega_U$) will be interfered by the undesired signal $s_{1,n}(k)$ ($k \in \Omega_D$) if $\hat{\epsilon}_1 \neq 0$ or $\hat{\tau}_1 \neq 0$; (2) The signal at subcarrier l, $z_m(l)$, is interfered by the desired signals from other subcarriers with $k \neq l$, if $\hat{\epsilon}_2 \neq 0$ or $\hat{\tau}_2 \neq 0$.

IV. Other problems in FBMC and OFDM duplexing

There are a few other problems in FBMC and OFDM duplexing.

(1) Interference from the transmitting signal. Since the device can transmit and receive at the same time, the received signal is interfered by the transmitting signal if the orthogonality is destroyed by the non-ideal radio. Note that in general the transmitting signal has much higher power than the received signal. Thus the interference to the received signal from the leakage signal can be large.

(2) Insufficient dynamic range. If the dynamic range of the signal is limited, the received signal may be saturated by the strong transmitting signal. The non-linear power amplifier will cause the signal distorted.

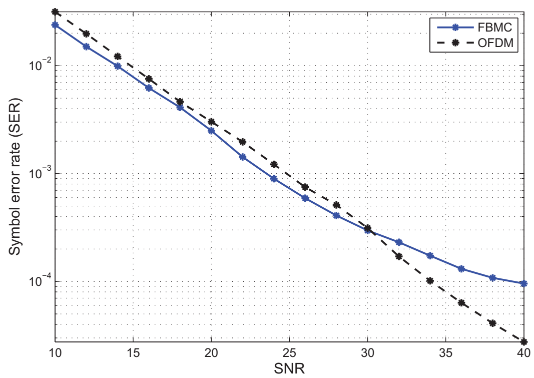

Fig. 2. SER vs SNR (BPSK, fully synchronized with both signals)

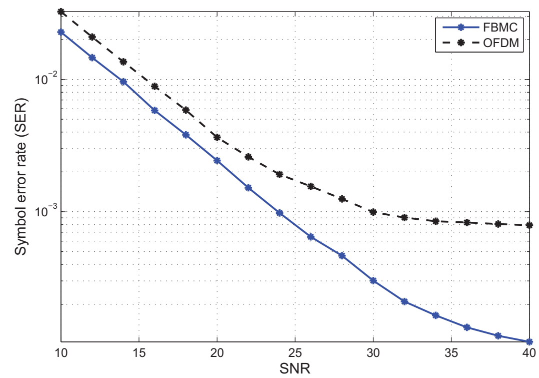

Fig. 3. SER vs SNR (BPSK, fully synchronized with transmitting signal; for desired signal: ϵ_{max} =1kHz, τ_{max} =10)

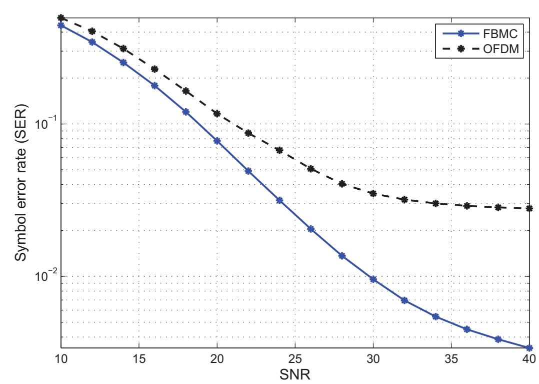

Fig. 4. SER vs SNR (16QAM, fully synchronized with transmitting signal; for desired signal: ϵ_{max} =1kHz, τ_{max} =10)

(3) Insufficient ADC resolution. The strong transmitting interference signal enlarges the dynamic range of the received signal and thus increases quantization noise with fixed ADC resolution.

(4) High PAPR. Both FBMC and OFDM have relatively high PAPR. Thus their output signals may be distorted by a power amplifier with non-ideal linearity.

The source of the first three problems is the much stronger transmitting (undesired) signal than the desired signal. This can be alleviated if the cell size is small. Recently small cell is emerged as one of the most promising technology for future wireless communications [10, 11]. Obviously if the cell size is small, the signal propagation loss will be much less. There are other means to reduce the interference strength. One possibility is to reduce the transmitting analog signal strength to the local receiver before the ADC of receiving. In [5], analog filters are used to moderate the transmitting signal before the ADC. Another approach is to use an isolator to isolate the transmitting signal to the local receiver [15]. It is shown in [15] that the isolator can reduce the transmitted signal power (received by the receiver at the same device) by as large as 85dB. However, the impact of such isolation to the desired (remote) receiver needs further investigations.

Advanced signal processing technologies can also be used to handle the interference problem. For example, in [2] interference cancelation and multiple antenna techniques are applied to realize full duplexing communications. With multiple antennas, approaches like beamforming can be used to reduce the transmitting signal interference to the local receiver. However, this will increase the system complexity dramatically.

V. Simulations

For fair comparison, we choose the FBMC system and OFDM system to have the same bandwidth efficiency. The prototype filter for FBMC is designed based on the IOTA (Isotropic Orthogonal Transform Algorithm) [12–14] with $TF = 1.25$. For OFDM, the CP length is chosen as $N/4$, where $N = 256$ is the number of subcarriers.

Among the 256 subcarriers, there are 43 null subcarriers to control the out-of-band emission. The data subcarriers are divided into 8 subchannels (subbands). As an example, 4 subbands are used for downlink and the other 4 subbands are for uplink. The subbands for downlink and uplink are interleaved. To reduce the interference, we also insert two null subcarriers at the edge of each subband.

We assume that the maximum residual CFO is ϵ_{max} kHz. The actual residual CFO at each Monte-Carlo test is randomly generated in $[-\epsilon_{max}, \epsilon_{max})$ with even distribution. The maximum residual timing error is τ_{max} samples. The actual residual timing error at each Monte-Carlo test is randomly generated in $[-\tau_{max}, \tau_{max})$ with even distribution.

We consider frequency selective channel with 65 taps for the desired signal. Exponential power delay profile with factor 0.1 is used for the channel. In the following, we assume that the transmitting (undesired) signal power is 20dB higher than the desired signal power.

We consider four cases: (1) Both transmitting and desired signals are fully synchronized; (2) Transmitting signal is fully synchronized, but desired signal is not; (3) Transmitting signal has timing error, while desired signal has timing and frequency errors; (4) Both transmitting signal and desired signal have timing and frequency errors. The results are shown in Figure 2 to 7, respectively, where BPSK and 16QAM modulations

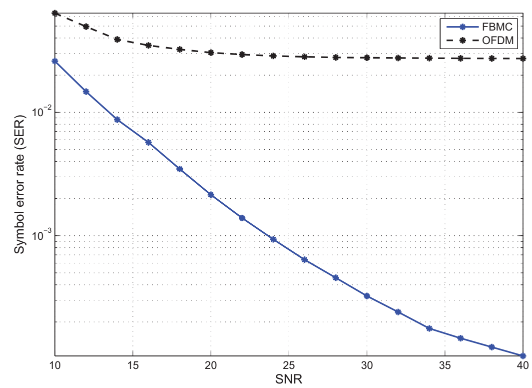

Fig. 5. SER vs SNR (BPSK, for transmitting signal: ϵ_{max} =0kHz, τ_{max} =2; for desired signal: ϵ_{max} =1kHz, τ_{max} =10)

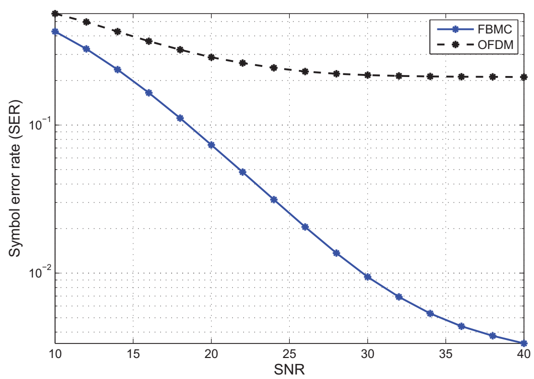

Fig. 6. SER vs SNR (16QAM, for transmitting signal: ϵ_{max} =0kHz, τ_{max} =2; for desired signal: ϵ_{max} =1kHz, τ_{max} =10)

are considered.

Based on the simulations, we have the following observations. (1) Synchronization with the transmitting (undesired) signal is very critical especially for OFDM duplexing, as OFDM is very sensitive to synchronization errors and the

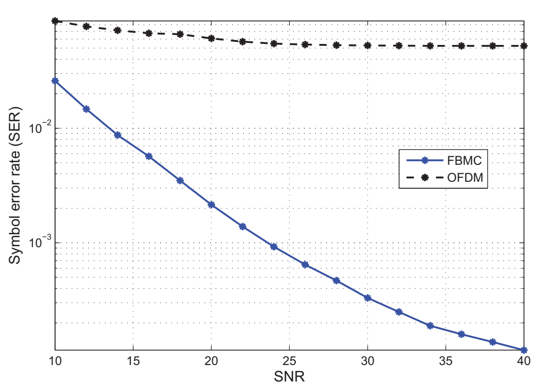

Fig. 7. SER vs SNR (BPSK, for transmitting signal: ϵ_{max} =2kHz, τ_{max} =5; for desired signal: ϵ_{max} =1kHz, τ_{max} =10)

transmitting signal power is much higher than the desired signal power. On the other hand, FBMC duplexing is much robust to such synchronization errors. (2) With relatively large synchronization errors in the desired signal, FBMC duplexing also has better performance than OFDM duplexing, even if full synchronization with transmitting signal is achieved.

VI. Conclusions

We have proposed a FBMC duplexing scheme in which downlink and uplink use the same FBMC structure with the same frequency band but different subcarriers. It is shown that FBMC duplexing has a few advantages but also some undeniable problems. Compared to OFDM duplexing, the major advantages of FBMC duplexing are its much better robustness to timing and frequency errors that are shown to be unavoidable in both schemes, and reduced number of null subcarriers to control the out-of-band emission. These make FBMC duplexing having advantages in applications like small cell, spectrum sharing, spectrum reuse and cognitive radio.

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