# Multicarrier-Division Duplex: A Duplexing Technique for Shift to 6G Wireless Communications

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***Abstract*—In-band full-duplex (IBFD) has the potential to not only double the spectral efficiency (SE) but also greatly reduce the transmission latency. However, the less maturity of existing self-interference cancellation (SIC) techniques renders IBFD impractical for future wireless applications. To inherit the merits of full-duplex (FD) but with practical SIC requirements, multicarrier-division duplex (MDD) was proposed and studied recently. In this article, we demonstrate the advantages of MDD over the IBFD mode and the conventional half-duplex (HD) modes of frequency-division duplex (FDD) and time-division duplex (TDD) from several essential aspects, including SIC capability, resource integration and the support for high-mobility communications. Several numerical results are included to show that MDD outperforms IBFD in terms of energy efficiency and SIC. Compared with the HD modes, MDD is capable of efficiently integrating the DL/UL resources to achieve higher SE and significantly outperforms TDD, when communicating over fast time-varying channels. Lastly, some implementation challenges of MDD systems are discussed.**

## I. Background

In recent years, the research for the 5G techniques motivating to improve spectral and energy efficiency (SE and EE) has been continuing to thrive. However, several techniques originally expected to be exploited in 5G, such as visible light communication (VLC), machine learning (ML) and in-band full-duplex (IBFD), are deemed to no longer stay in the blueprint of 5G, but may be possibly applied to 6G systems instead. Among the aforementioned potential techniques, IBFD, as a promising duplex mode leveraging the whole time/frequency resources, explicitly has the high priority for application in the future wireless communication systems. Unfortunately, the self-interference (SI) problem, which hindered IBFD from becoming one of the pillars in 5G, is still the main obstacle for applying IBFD to 6G, due to the paucity of efficient and low-complexity SI cancellation (SIC) techniques [1]. More specifically, to make IBFD feasible, SI should be efficiently mitigated in the propagation-, analog- and digital-domain to the level of background noise. However, the overall SIC capability is subject to the constraints of hardware/software complexity, system power, SI channel estimation, etc. According to [2, 3], IBFD systems are extremely susceptible to the SIC capability. Insufficient SIC can cause significant degradation of system performance, rendering IBFD to lose its advantages against the conventional half-duplex (HD) modes counterparts. Moreover, the applications of ultra-massive multiple-input multiple-output (MIMO) and terahertz (THz) communications in 6G may impose further burden on SIC, resulting in new challenges for the practical deployment of IBFD.

A question naturally arises as to if the hardware/software technologies fail to provide the desired SIC for the practical implementation of IBFD in near future, *is there a transitional alternative from HD to IBFD, which can not only inherit the main merits of IBFD but also relieve the stringent requirements of IBFD for SIC?* To this end, the multicarrier-division duplex (MDD), originally proposed in [4], and recently studied in [3, 5], is capable of enabling concurrent downlink (DL) and uplink (UL) transmissions in the same time slot and same frequency band, but on different subcarriers. To achieve these, in MDD systems, the subcarriers of one band are divided into two mutually exclusive subsets, namely a DL subcarrier subset and UL subcarrier subset, to support DL and UL transmissions, respectively. Thanks to its features, MDD enjoys a host of merits in terms of its implementation, channel state information (CSI) acquisition, and communication efficiency, some of which are summarized as follows:

First, since each subcarrier is assigned for supporting either DL or UL, MDD allows a receiver to be nearly free of SI in digital domain by relying only on the fast Fourier transform (FFT) processing. In other words, in MDD systems, only the propagation- and analog-domain SIC are needed to suppress SI. By contrast, in IBFD multicarrier systems, DL/UL transmissions happen simultaneously on each subcarrier. Hence, SIC in digital domain is essential, which complicates the system design and increases the cost of implementation. Therefore, the inherent features of MDD can enable 6G systems to benefit from the FD-relied operations, while with relatively low implementation complexity and power consumption.

Second, it is beneficial to aggregate the DL and UL resources that are separately used in time-division duplex (TDD) and frequency-division duplex (FDD) systems. With the joint resource allocation (RA) among all the users communicating on DL and UL, MDD can not only improve the resource utilization, but also significantly enhance the efficiency of communications via exploiting the embedded multiuser diversity and subcarrier diversity. Furthermore, guard period/band are no longer needed in MDD systems, which can further improve efficiency by reducing overhead.

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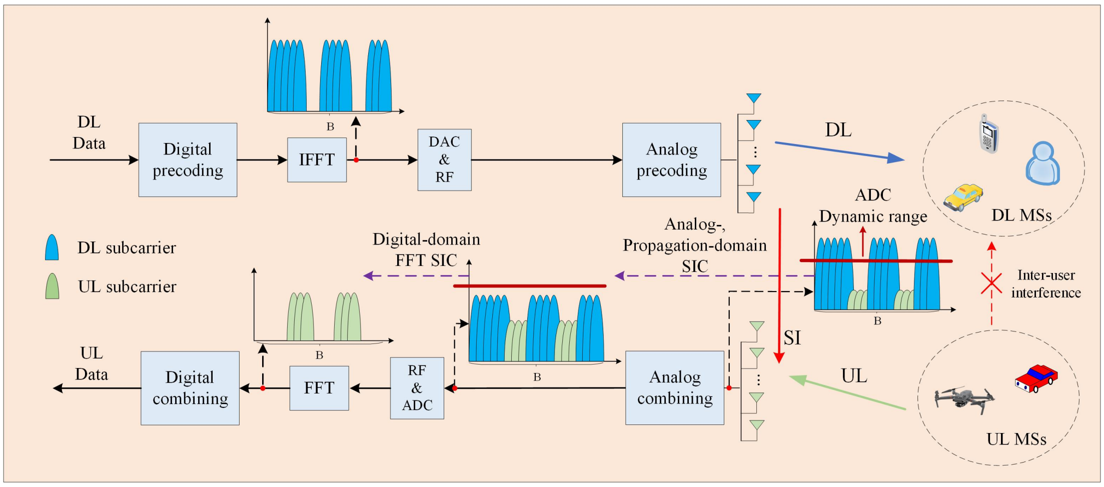



Fig. 1. SIC processing in MDD-MIMO systems with hybrid beamforming.

Third, it is a highly flexible duplex scheme for supporting symmetric, asymmetric and variable-rate traffic demanded by the different users on UL and DL. Straightforwardly, this can be achieved by dynamically allocating the corresponding numbers of subcarriers to the users having different rate and QoS requirements.

Fourth, it is suitable for operation with various multicarrier schemes, including conventional orthogonal frequency-division multiplexing (OFDM) and single-carrier frequency-division multiple access (SC-FDMA), filtered OFDM, filter-bank multicartrier (FBMC), orthogonal time-frequency space (OTFS) modulation, etc. It is also flexible for integrating different multicarrier schemes to provide feasible solutions for the evolution of 5G systems to 6G systems.

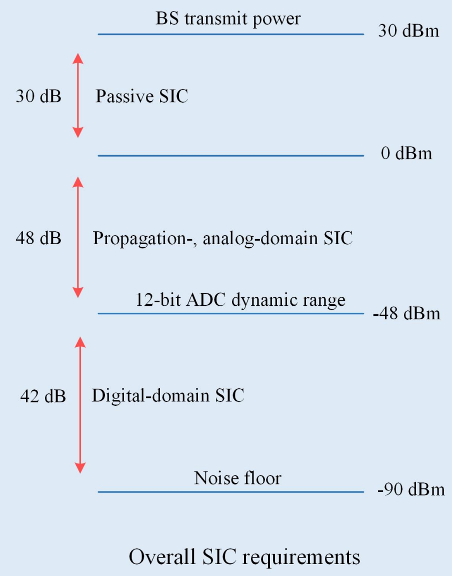
Last but not the least, employing MDD enables systems to mitigate the channel aging problem in high-mobility communications, which is a paramount application scenario considered in 6G. Since in MDD systems, DL/UL transmissions occur at the same time on different subcarriers, UL pilots can be continuously or frequently transmitted during DL transmissions, so that the CSI can be updated in time and will not be outdated as in TDD systems.

In the rest of this article, considering some practical application scenarios and specific system designs, we will make a comprehensive comparison of the MDD, IBFD and HD modes from several aspects that are regarded to be critical in the implementation of 6G systems.

## II. MDD Vs IBFD: Energy Efficiency Resulted from SIC

Figure 1 illustrates the SIC processing in MDD-MIMO systems. From this figure, it can be observed that DL/UL transmissions relying on different sets of subcarriers within one band can occur simultaneously within the same OFDM symbol duration. However, as the receiver is very close to the transmitter at BS side, the UL signal at receiver antennas is overwhelmed by the DL signal, the power of which may significantly exceed the available dynamic ranges of analog-to-digital converters (ADCs). Hence, in order to enable ADCs to work efficiently and avoid large quantization noise, both IBFD and MDD systems have to resort to the propagation/analog-domain SIC, so that the signal prior to entering ADCs is limited within their efficient dynamic ranges. After the ADC processing, the conventional IBFD systems have to further mitigate the residual digital-domain SI by first reconstructing the digital-domain signal between BS's DAC and ADC, and then subtracting it from the received signal [1]. However, the performance of the existing digital-domain SIC largely hinges on the estimation of SI channel and the reconstruction of SI signal, which are power-consuming and infeasible for implementation in the green communication networks. Furthermore, they are impractical to the small access points (APs) powered by batteries, such as, unmanned aerial vehicle (UAV), Internet of things (IoT) gateway, etc. By contrast, as its counterpart, MDD systems only rely on FFT operation to easily remove the residual SI in digital domain. Besides, it is noteworthy that for the mobile-stations (MSs) in MDD systems, the inter-user interference (IUI) from UL MSs on the DL MSs can be ignored in Figure 1. This is because the IUI and desired signal received by a DL MS are on the mutually orthogonal subcarriers, which is similar to the SI at BS. Hence, as the result of the large-scale fading of MS-MS link and MS's relatively low transmit power, IUI belongs to the low-power SI. Consequently, when all MSs and BS are assumed to be synchronized within an allowable time-window, the IUI can be ideally cancelled with the aid of the FFT operation in digital domain, as above-mentioned. Analogously, in the dense networks with multiple APs, e.g. cell-free networks, the APs operated in MDD mode can also be free of inter-AP interference (IAI)[1]. In principle, the reduced IUI or IAI in

[1]The suppression of IUI or IAI in MDD systems depends on the time synchronization (TS) [3]. In practice, the TS among APs is relatively easy to achieve via wired backhaul, while the TS among MSs is relatively challenging. The excessive TS error beyond the allowable time-window may cause the reduced performance of the FFT-relied SIC. The detailed analysis of the impact of TS on IUI mitigation will be studied in technical paper. Note that in this paper, we ignore the IUI in IBFD systems in the following comparison, although the effect of IUI in IBFD systems is much severer than that in MDD systems.




| Parameter | | Value |
|---|---|---|
| Number of DL/UL MSs | | 4/4 |
| Number of DL/UL subcarriers | | 64/32 |
| Tx/Rx antennas at BS | | 128/32 |
| Tx/Rx RF chains | | 16/8 |
| $P_{\text{BS,Tx}}$ | | 30 dBm |
| $P_{\text{MS,Tx}}$ | | 15 dBm |
| $P_{\text{BS,Cir}}$ | IBFD | 38 dBm |
| | MDD | 33 dBm |
| $P_{\text{SIC}}$ | IBFD | 23 dBm |
| | MDD | 20 dBm |
| $P_{\text{MS,Cir}}$ | IBFD | 18 dBm |
| | MDD | 15 dBm |
| Carrier center frequency | | 5 GHz |
| Subcarrier bandwidth | | 15 KHz |
| Noise floor | | -90 dBm |
| Path loss | | $R^{3.8}$ |
| The distance between BS and MSs (R) | | 100 m |

Simulation parameters

Fig. 2. Specifications for the SIC in MDD systems.

MDD systems will lead to the increased SE.

To analyse the advantages of MDD over IBFD in terms of the SIC capability in depth, we assume a MU-MIMO hybrid beamforming system as shown in Figure 1. The SIC requirements are presented in Figure 2. Generally, in FD systems, a certain amount of SI suppression can be obtained through passive approaches, including antenna-separation, cross-polarization, directional antenna, etc. In Figure 2, we assume a 30 dB of passive SIC, which can usually be achieved in practical FD systems [6]. Also, we assume that the 12-bit ADCs, whose effective number of bits (ENOB) is 9, are used at receiver, yielding an effective dynamic range of $6.02(\text{ENOB}-2) \approx 42$ dB [7]. Therefore, the maximum input power of ADC is limited to -48 dBm, when assuming a noise floor of -90 dBm. In other words, the digital-domain SIC can only suppress SI up to the effective range of ADC. Once the passive and digital-domain SIC are fixed, from Figure 2, the demand on the propagation- and analog-domain SIC can be easily calculated, which is 48 dB in our considered example. To suppress this SI, the adaptive beamforming-assisted method proposed in [5] may be applied, which is capable of providing a big range of SI suppression at the cost of slight performance degradation[2].

Although MDD and IBFD have nearly the same SIC requirement, when both systems have the same configurations, including transmit power, antenna deployment, ENOB of ADCs, etc., the SIC in the two modes yields different power consumption, leading to a big gap in terms of EE. In detail, firstly, unlike the IBFD using all the subcarriers for DL transmission, DL data in MDD systems is only transmitted on a portion of subcarriers, which can hence relieve the peak-to-average power ratio (PAPR) problem. Consequently, a corresponding IBFD system has to provide more analog-domain SIC to ensure that the SI signal is within the maximum range allowed by ADCs, which results in an increased power consumption. Secondly, BS needs to spend a certain amount of computation effort for digital baseband processing, which is a function of the number of subcarriers and data streams involved [8]. Hence, the power consumption incurred by the digital-domain signal processing in IBFD systems is much higher than that in MDD systems. Last but not the least, as shown in Figure 1, MDD can suppress the residual SI in digital domain by FFT operation without any additional overhead. By contrast, IBFD has to spend extra power and computation effort to estimate the channel between the DAC at transmitter and ADC at receiver, so as to reconstruct the originally transmitted signal for the SIC purpose.

According to the above discussion, we introduce a linear power model [9], with the total power consumption at BS expressed as

$$P_{\text{A,tot}}^{\text{B}} = P_{\text{A,Tx}} + P_{\text{A,Cir}}^{\text{B}} + P_{\text{SIC}}^{\text{B}} \tag{1}$$

where A $\in$ {BS, MS}, B $\in$ {IBFD, MDD}, $P_{\text{Tx}}$ denotes the transmit power, $P_{\text{Cir}}$ denotes the power consumption of both basic circuit blocks and SIC circuits, $P_{\text{SIC}}$ denotes the amount of power consumed for the SIC implemented in the analog- and digital-domain. Note that the term $P_{\text{SIC}}$ only appears when A $=$ BS, as MSs are assumed to operate in HD mode in Figure 1. Note that for short range communications, such as in microcell, picocell and indoor femtocell, the circuit power consumption is comparable to or even higher than the transmit power [10]. Then, the overall SE and EE can be denoted as

$$\text{SE} = \frac{1}{M}(R_D + R_U), \ \text{EE} = \frac{\text{SE}}{P_{\text{BS,tot}} + P_{\text{MS,tot}}} \tag{2}$$

where $M$ denotes the total number of subcarriers, $R_D$ and $R_U$ denote the DL and UL sum rates, respectively.

[2]For the readers interested in the effect of SIC on MDD system's performance, please refer to [3, 5].

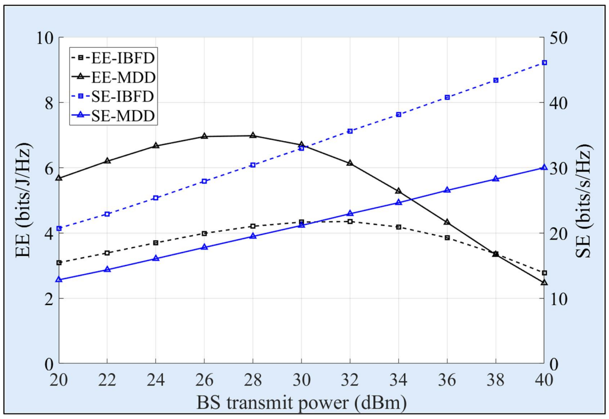



Fig. 3. EE and SE versus BS transmit power, where DL/UL communication channels are assumed to be the 4-tap channel with each tap following the complex Gaussian distribution of $\mathcal{CN}(0, 1/4)$, while the SI channel is flat Rician-fading due to the short propagation distance, whose detailed mathematical expression can be found in [5], with the Rician factor being 20 dB and the array angle between transmitter and receiver being 120°. The remaining parameters are presented in Figure 2. Note that, the power consumption of SIC and that of related circuits are set based on [9–11], which are assumed to be nearly invariant in the BS transmit power range considered. This is because the extra SIC requirement caused by the increased BS transmit power can be met in analog domain by running more iterations of the SIC algorithm proposed in [5] at ignorable energy.

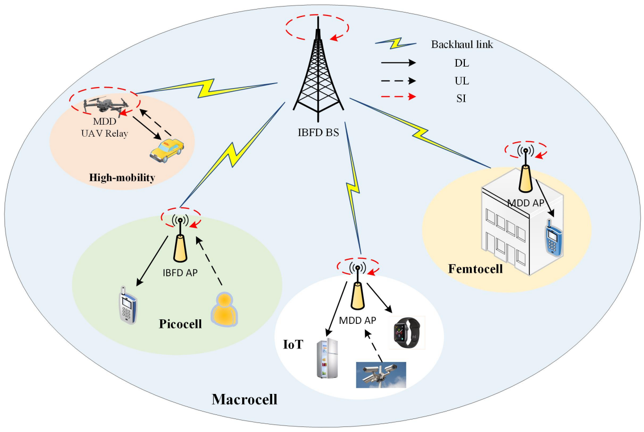



Fig. 4. The heterogeneous network supported by both IBFD and MDD systems, where relatively low-power sub-networks are supported by MDD, while the communications between relatively high-power AP and BS are supported by IBFD.

From Figure 3, we can observe that, the IBFD system using all the subcarriers for simultaneous DL/UL transmission outperforms the MDD system in terms of SE. However, subject to the higher power consumption caused by the implementation of more data streams and digital-domain SIC, IBFD system has significantly lower EE, until the BS transmit power reaches 38 dBm, which can be explained as follows. As the BS transmit power increases, owing to the full usage of subcarriers, the SE gap of IBFD over MDD increases, which makes the EE of IBFD system finally surpass that of MDD system. Hence, in practical deployment, for the high-power BSs, e.g., Macro BS and Micro BS, or APs having the demand of high sum rate, while without the burden of implementation complexity, IBFD is a promising mode. By contrast, for those small APs that are subject to the constraints on energy consumption and system complexity, MDD provides a desirable alternative, so as to enable the FD-relied functions without much increase of overhead. Additionally, in the interference-limited systems with dense deployment of APs and MSs, MDD can be expected to be a better option owing to its advantage of IAI and IUI suppression. Therefore, these two modes may be simultaneously implemented in a heterogeneous network as shown in Figure 4, where each terminal can choose either MDD or IBFD depending on the constraints on power consumption and the QoS of users.

## III. MDD Vs HD: Integration of DL/UL Resources and High-Mobility Wireless Communications

Straightforwardly, IBFD employs the capability of integrating the time/frequency resources for supporting simultaneous DL/UL transmissions. However, as analysed in the last section, before the IBFD is made practically implementable with low power consumption and low complexity SIC mechanisms, MDD can be a promising transitional technique from HD to IBFD. Nevertheless, people may argue that *MDD system separates the spectrum into two groups of subcarriers to render FD operation. However, it is unable to double the SE as IBFD system can potentially do. Instead, it experiences SI in analog domain, leading to the extra complexity burden when compared with TDD or FDD-based HD system. Whether is it worth the effort?* To address this concern, in the sequel, we consider the resource usage and the communications over fast time-varying channels.

### A. Resource Allocation

Figure 5 demonstrates the flexibility of MDD system in RA scenarios and shows the advantages of MDD over the conventional TDD/FDD modes. Firstly, as depicted in Figure 5, three systems are assumed to support the same number of UL/DL users with the same time-frequency resources. However, TDD/FDD have to add guard period/band to avoid the conflict between DL/UL transmissions, which leads to the waste of resources. By contrast, MDD system operated in FD mode is capable of getting rid of the switching protection between DL/UL, and hence can increase the SE in comparison with the TDD/FDD relied systems. Furthermore, from Figure 5, we can observe that during the processing of RA, when 10 DL MSs and 10 UL MSs are supported and when the unfair greedy algorithm is employed, each resource element in MDD system can be assigned to either a DL MS or a UL MS. Hence, the achievable multiuser diversity order is 20. By contrast, in TDD/FDD systems, as BS is operated in HD mode and a specific resource block is fixed for either DL or UL, the multiuser diversity order is at most 10. Therefore, the MDD system jointly distributing subcarrier resources among DL/UL MSs is capable of improving the efficiency of resource usage, resulting in the further increase of capacity. In Figure 6, when assuming that DL/UL are ideally separated in TDD/FDD modes and hence no guard period/band, i.e., $\eta = 0$, we can see that MDD system achieves the highest SE, thanks to its larger multiuser diversity gain. Furthermore, when $\eta = 1/16$

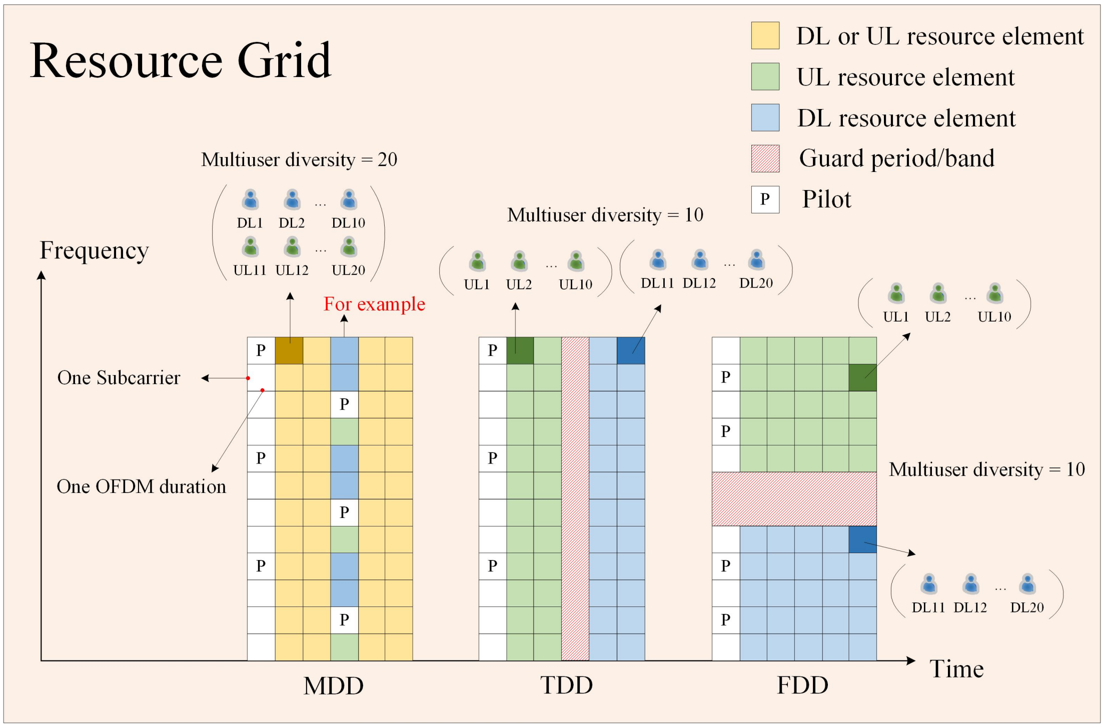



Fig. 5. The resource grid in MDD, TDD and FDD systems.

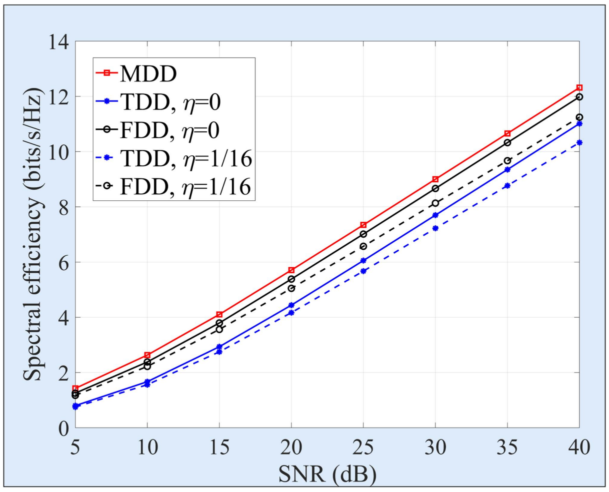



Fig. 6. Comparison of SE achieved by MDD, TDD and FDD modes. A MU-SISO OFDM system is considered and the number of DL/UL MSs, OFDM data symbols, and subcarriers are 10/10, 16 and 256, respectively. In MDD system, the SI is assumed to be suppressed below the noise floor, while in FDD and TDD systems, the proportion of guard period/band is $\eta$. The Gaussian noise has the variance of $1/\text{SNR}$. Moreover, the unfair greedy and water-filling algorithms are applied for multiuser scheduling and power allocation, respectively.

is introduced, implying the decrease of available resources for data transmission in TDD/FDD modes, the performance gap between MDD and TDD/FDD systems further enlarges.

Secondly, in multicarrier OFDM systems, pilots are usually equally distributed in the frequency band, as shown in Figure 5, and the estimated CSI is then used to serve for a coherence block, whose size is about $B_cT_c$, where $B_c$ and $T_c$ denote the coherence bandwidth and coherence time, respectively. Currently, the TDD mode, which leverages the channel reciprocity between DL and UL, dominates in massive MIMO systems. However, as shown in Figure 5, the requirement of switching periods may largely limit the system performance of TDD systems. This can be seen that when either $B_c$ or $T_c$ decreases due to environment changing, it causes the size of coherence block to shrink. As the result, the channel estimation needs to be operated more frequently to update CSI, which increases the switching frequency and hence reduces the sum rate in the long run. In the extreme case, when channel varies too fast, making $B_cT_c$ be too small, TDD mode may even become invalid to provide reliable CSI for the operation of massive MIMO systems. As for the FDD mode, although DL/UL can be operated concurrently, the channel reciprocity is hard to achieve, since DL band is usually separated far away from the UL band. Hence, in the FDD systems, using CSI for DL transmission imposes a large burden on the MSs for channel estimation and the backhaul resources for feeding back CSI to BS. Due to these considerations, the feasibility of FDD in massive MIMO based 5G+ and ultramassvie MIMO based 6G networks is highly dubious [12].

On the other side, the MDD mode can take the advantages of the correlation existing among the DL/UL subcarriers to implement channel estimation like TDD. Moreover, it enables DL, UL and pilots to be located within one OFDM symbol duration but on different subcarriers, as shown by the example in Figure 5. Owing to this configuration, the CSI for data transmission is possible to be updated whenever it is needed, at no expense of increasing the switching period, as the TDD mode. Furthermore, at the network level, a MDD-relied node is allowed to receive signals from user plane and control plane concurrently, which is capable of decreasing the access latency and boosting the operation speed of the overall network.

Additionally, we can know from Figure 5 that the asymmetric communications can be easily achieved in MDD systems by allocating different numbers of subcarriers to DL and UL. In comparison with the TDD systems that control the DL/UL capacity ratio through time-slot allocation, MDD systems may attain a more stable capacity ratio, as its asymmetry is implemented at the OFDM symbol level and not affected by the time-varying channels. By contrast, FDD systems are usually more suitable for supporting symmetrical UL/DL traffics, whereas it cannot be dynamically configured for obtaining different capacity ratios, due to the fixed assignment of UL/DL frequency bands.

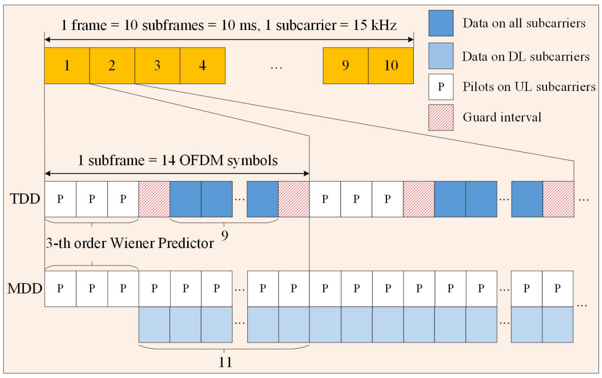



Fig. 7. TDD and MDD frame structures for high-mobility communication scenarios.

## *B. Communications over Time-Varying Channels*

With the rapidly growing demand for high-mobility services in, such as, ground vehicles, high-speed trains, UAVs, etc., the reliability of CSI is no longer dominated by pilot contamination but by channel aging. That is to say that in high-mobility scenarios, as the result of fast time-varying, the channel estimated during UL training may become outdated at the time when it is applied, resulting in significant performance degradation. Moreover, in future wireless systems, both BS and MS are expected to be equipped with the large-scale antenna arrays for attaining the required capacity, which pose further challenges on the CSI acquisition, especially, in the fast time-varying communication environments. As the only feasible duplex mode considered so far for practical massive MIMO systems, TDD can perform well in low-mobility scenarios. However, it deteriorates quickly with the increase of mobility even when highly efficient channel prediction approaches are introduced [13, 14]. The main reason behind is that in TDD-based systems, the pilots transmitted via UL at the beginning of a transmission period are used to serve the subsequent detection of UL data and DL transmission. Under this design, if channel varies fast, it becomes increasingly difficult to be predicted with an acceptable accuracy, when DL/UL symbols are far away from pilots. To overcome this problem, more pilots may be inserted during data transmission so as to renew the CSI. However, doing so would introduce more switching intervals and also increase system complexity, leading to the decrease of both SE and EE. Due to the above-mentioned issues, it has been recognized that TDD is not suitable for supporting high-mobility wireless communications, especially, in massive MIMO systems [14].

As shown in Figure 5, in MDD systems, DL/UL data and pilots can be simultaneously transmitted within one OFDM symbol duration. Hence, the CSI for UL detection and DL transmission can be refreshed whenever needed. Owing to this feature, MDD can be a promising alternative for supporting wireless communications over fast time-varying channels. We may argue that in MDD systems, pilots are transmitted at the sacrifice of the available subcarriers for DL transmissions. In this regard, IBFD can be a better option if sufficient SI suppression can be provided by low-cost and low-complexity SIC methods. However, to date, the existing SIC approaches for IBFD are unable to meet the demand. Needless to mention that in the high-mobility scenarios, SIC becomes even more challenging. Therefore, when considering the trade-off among all the related factors into account, MDD may be the best option for the near-future wireless systems, before a practical IBFD system is available for high-mobility communications.

To compare the performance of MDD and TDD in high-mobility scenarios, we refer to the numerology 0 of the 5G frame structure [15] and design the MDD and TDD frames for DL transmissions. As shown in Figure 7, 3 pilots are initially transmitted for the channel estimation in both MDD and TDD systems. Then, for BS to estimate CSI, we assume a 3-rd order Wiener Predictor (WP), which predicts the CSI for serving the following symbols. Generally, when operated in low-mobility scenarios, in order to avoid the waste of resources, the pilots in TDD may only exist in some pre-defined subframes [15]. However, as we can observe in Figure 8(a), the accuracy of channel prediction drops dramatically with the increase of symbol index (time), and the situation becomes worse, when the relative speed between BS and MSs increases. Based on the above observation, we now consider two training strategies for TDD, one transmits 3 pilots once in every subframe and the other one transmits 3 pilots once in every two subframes. Straightforwardly, employing a higher order WP or more training phases can lead to more accurate CSI prediction, it however also reduces the duration for data transmission. Therefore, we need to strike a good balance for TDD frame structure in terms of the insertion of pilots and achievable data rate, which deserves further study. For the CSI acquisition in MDD systems, we consider an extreme case, where pilots are continuously sent by MSs. Hence, the 3-rd order WP always has the latest observations to predict the CSI required for DL transmission. Figure 8(a) shows that the prediction accuracy can be sustainable and nearly time-invariant.

Figure 8(b) compares the system's average sum rate, showing that MDD significantly outperforms TDD over fast time-varying channels. Explicitly, the performance gap increases, as channel varies more rapidly. Besides, the TDD system with less frequent training within one frame performs well in low-speed scenarios. When the velocity goes higher, more frequent training is needed to achieve better performance. However,

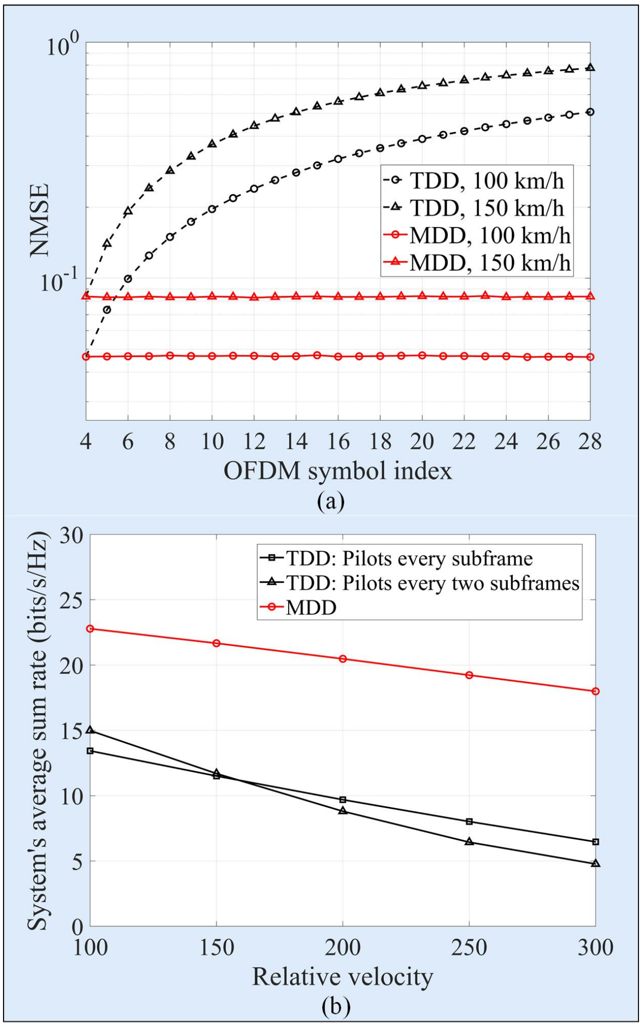



Fig. 8. Comparison of MDD and TDD in high-mobility scenarios: a) Prediction accuracy in terms of normalized mean squre error (NMSE) versus OFDM symbol index; b) Achievable average sum rate versus the relative velocity between BS and MSs. For simulations, we assume a MU-MIMO full-digital system with zero-forcing precoding, where a BS equipped with 32 antennas supports 4 single-antenna MSs operated in MDD mode, and SI is assumed to be suppressed under the noise floor. The numbers of DL/UL subcarriers are 128/16, $P_{\text{BS,Tx}} = 40$dBm, $P_{\text{Ms,Tx}} = 30$dBm. The OFDM symbol duration with CP is $71.35\mu s$. As for channel aging, we adopt the Jakes model with an autoregressive model of order 1 [13]. Channel estimation is based on the approach proposed in [5]. Finally, the communication channels, pathloss and BS-MS distances are set the same as those set in Figure 2.

in both cases, TDD becomes less efficient, as channel varies faster.

To this point, we should note that in practice, the MDD mode would not be operated in this extreme case, as shown in Figure 7. Rather, it can activate the corresponding numbers of pilots according to the real levels of channel aging. For instance, when channel variation becomes relative slow, thus making it unnecessary to always transmit pilots, some training resources may be released for DL data transmissions, which in turn further enhance the throughput of MDD systems.

## IV. Implementation Challenges of Multicarrier-Division Duplex

MDD employs a range of merits, as analyzed above, which provide us opportunities to meet the requirements of the 5G+ and 6G wireless systems. However, opportunities often lead to challenges in practical implementation. MDD is specifically designed for multicarrier systems. Hence, depending on the specific multicarrier scheme employed, such as, OFDM, SC-FDMA, FBMC, time-frequency-packed multicarrier (TF-PMC), etc., it may have the common technical challenges, such as the effect of frequency offset, time offset, etc. Furthermore, as MDD is an out-band FD scheme for multicarrier communications, the following direct challenges should be addressed in implementation.

First, like TDD systems, MDD systems also put a high demand on synchronization of all the terminals. Otherwise, the relative delays existing between the signals sent by different terminals may generate inter-carrier interference or/and multiuser interference. The demand on synchronization in MDD systems may be relaxed with techniques which are robust to synchronization errors. For example, if time-domain direct-sequence spreading is introduced to form multicarrier direct-sequence code division multiple access (DS-CDMA), the interference generated by the non-ideal synchronization may be significantly reduced after the despreading operation at receiver. Furthermore, when the estimations of relative delays and other CSI are available, employing advanced multiuser detection or/and interference suppression can also relax the stringent synchronization requirement.

Second, as mentioned in Section II, MDD systems are nearly free from digital-domain SI, which accounts for a large portion of the total SI. Hence, in MDD systems, the implementation of propagation- and analog-domain SIC is as critical as that in IBFD systems. In [5], a beamforming-based SIC algorithm was proposed for the separate-antenna large-scale MIMO system, which is feasible for practical implementation in terms of complexity and system performance. However, for the shared-antenna systems or small-size wireless terminals like smartphones, some IoT devices, etc., operated in MDD mode, the multi-antenna beamforming-based SIC techniques are not practical. Instead, the analog-domain SIC techniques of low complexity, power consumption and small form factor are required. One possible solution is that if blocks of UL subcarriers are separated between adjacent blocks with sufficient DL subcarriers, the analog-domain filters may be applied to significantly suppress the power of DL subcarriers, i.e., SI, to make sure that the received UL signals successfully pass through the receiver ADC. Then, the residual SI is further suppressed in digital domain.

## V. Conclusion

To demonstrate the potentials of MDD for the future 5G+ or 6G wireless systems, we firstly made a comparison between IBFD and MDD in terms of SIC, showing that in comparison with IBFD, MDD renders the FD-relied operations more energy-efficient and feasible for implementation. Then, we explored the advantages of MDD over the HD modes of

TDD/FDD with respect to RA. As MDD facilitates DL/UL resource integration, a higher multiuser diversity gain than TDD/FDD can be attained and unnecessary guard band/period can be avoided, which hence contribute to the higher SE of MDD systems. Furthermore, MDD can take the advantages of FD for designing the communication schemes suitable for high-mobility scenarios. Thanks to the simultaneous UL/DL transmission, MDD can relieve the channel aging problem in fast time-varying channels. Finally, several implementation challenges of MDD systems are highlighted.

## ACKNOWLEDGMENT

We would like to acknowledge with thanks the financial support from the EPSRC, UK, under the Projects EP/P034284/1 and EP/P03456X/1.

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