Technical White Paper

XDD (Cross Division Duplex): Extending Coverage of 5G TDD Carriers

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Standards Research Team
Samsung Research

Contents

Introduction

Recently, the first release of the fifth-generation (5G) standard, called New Radio (NR), was completed in the 3rd Generation Partnership Project (3GPP). Compared to fourth-generation (4G) Long Term Evolution (LTE), 5G NR supports operation on higher carrier frequencies up to tens of GHz, a larger bandwidth up to 400 MHz, and a larger number of mandatory receiver antennas up to 4 at the terminal (called UE in 3GPP) to meet higher requirements. Due to the higher frequency bands used for 5G in order to support wider bandwidths, one critical issue identified during the initial deployment of NR systems was the limited coverage.

The key factor that impacts the NR coverage is that majority of the new 5G spectrum allocations around the globe are time-division duplex (TDD) carriers located around 3.3 - 3.8 GHz, 28 GHz, or 39 GHz which are much higher than that of 4G (Fig.1). TDD has a number of advantages over frequency division duplex (FDD). Since TDD uses the same frequency resources for downlink (DL) and uplink (UL), channel reciprocity can be exploited to allow base stations (called gNB in 3GPP) to estimate the downlink channel based on the measurements on the uplink channel. Another advantage is that TDD can handle asymmetric downlink and uplink traffic ratio more efficiently. Typically, there is more downlink traffic compared to uplink traffic due to applications such as video streaming. TDD handles such asymmetry in downlink and uplink traffic by allocating more time resources for downlink and less for uplink. While assigning more time resources for downlink has its benefits, there is a key disadvantage. By assigning the majority of time resources to the downlink, only a small portion of time resources can be allocated to the uplink which limits the energy that can be accumulated to result in a reduced uplink coverage.

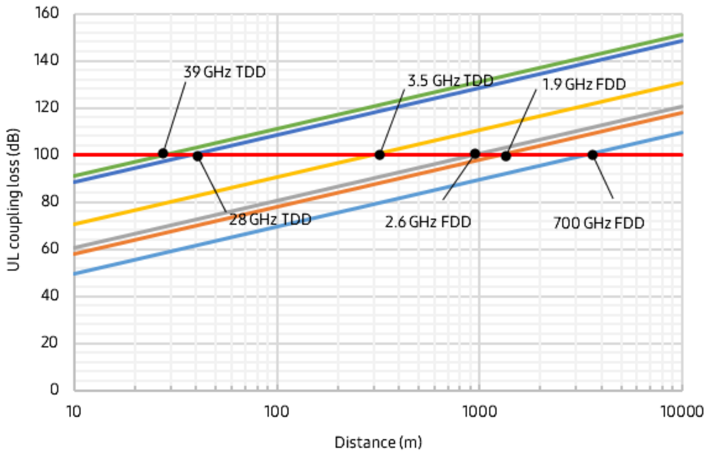


Fig. 1 Uplink coupling loss due to frequency and duplex scheme: a decrease in transmission time due to TDD (e.g., 7 dB degradation with 20% duty cycle) and a larger signal attenuation (free-space pathloss) due to higher carrier frequency

Cross division duplex (XDD) is a new duplexing technology that provides enhanced coverage, capacity, and latency over conventional TDD. Instead of relying solely on orthogonal time resources for DL-UL separation, XDD adds the use of non-overlapping frequency resources within a carrier bandwidth. By separating downlink and uplink in the frequency domain, the need for DL-UL separation in the time domain is no longer necessary. Hence, in XDD, it is possible to allow both downlink and uplink to have full access to the time resources and thereby avoiding drastic reduction in uplink coverage as in TDD. Another benefit of XDD is that a downlink or uplink transmission can be made at any time and can reduce the latency in the overall operation of 5G cellular operation. The benefits of XDD are not without cost. XDD requires a base station transceiver implementation that can handle self-interference as well as advanced management and mitigation of cross-link interference (CLI).

Scope of this paper

This paper provides a high level description of XDD concept, benefits, and implementation challenges. First, an overview of XDD is provided that includes a comparison with conventional TDD and FDD. Next, the implementation challenges of XDD especially at the base station to handle self-interference mitigation is provided. Furthermore, several features that we consider critical in realizing XDD in actual deployment scenarios are provided along with some performance results. Finally, Samsung's view on XDD for the next phase of 5G evolution (5G-Advanced) is provided.

Overview of XDD (Cross Division Duplex)

Before starting the discussion on XDD, it should be worthwhile to briefly summarize the conventional duplexing schemes used in 3G, 4G, and 5G cellular systems.

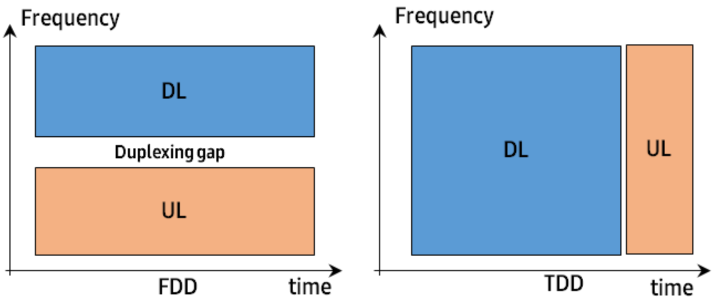


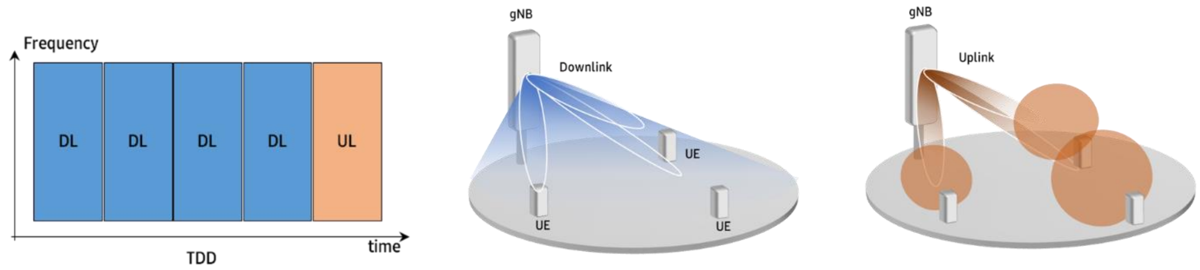
Fig. 2 Comparison between FDD and TDD

In early cellular systems such as 3G, FDD was widely used due to the narrowband nature of wireless signals and the symmetry of downlink and uplink traffic in voice telephony which was the dominant application at the time. In FDD, the downlink and uplink use dedicated and disjoint frequency resources as shown in Fig. 2. The frequency resources are separated considerably so as to avoid mutual interference between the downlink and uplink signals. One key benefit of FDD is that both downlink and uplink can have full access to the time resources to maximize coverage. A downside of FDD is that there is no flexibility to shift frequency resources in downlink or uplink. Frequency resources for downlink and uplink in FDD are fixed.

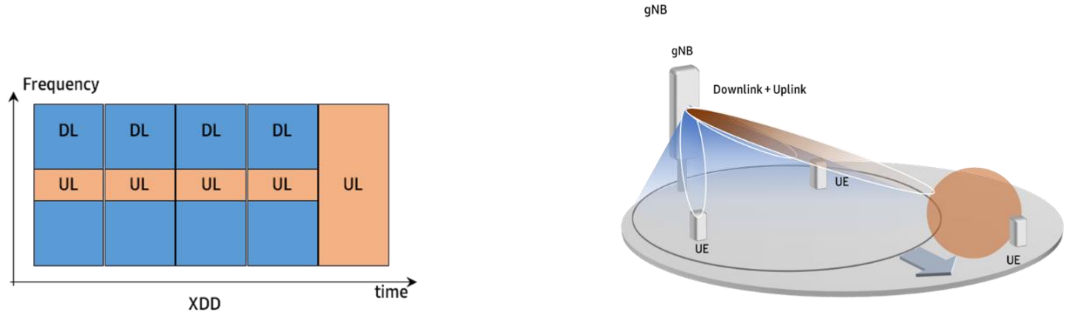
In contrast to FDD, TDD uses the same frequency resources for downlink and uplink. Instead of dedicated and disjoint frequency resources to separate downlink and uplink, it relies on dedicated and disjoint time resources as shown in Fig. 2. In TDD, neither downlink nor uplink can have full access to the time resources and therefore has a reduced coverage compared to FDD.

Although TDD was introduced to supplement FDD in 3G, it was not as widely deployed. However, with wireless traffic expanding exponentially, especially due to downlink heavy applications such as video and wireless internet, the benefits of TDD became evident. For TDD, it is possible to assign more time resources to either downlink or uplink depending on the needs of the network. While TDD could be optimized this way, it was not possible to so for FDD. Due to such limitation, for many of the commercial 4G networks utilizing FDD, uplink frequency resource is often underutilized while the downlink frequency resource is under heavy use. In 5G, most of the new spectrum bands being assigned are TDD carriers making it easier to address the asymmetric nature of downlink and uplink traffic. However, TDD's fundamental problem of coverage limitation when compared to FDD still remains.

What is XDD?



(a) Conventional TDD system (time division for downlink and uplink period)



(b) XDD system (frequency division for downlink and uplink period)

Fig. 3 The concept of XDD (with compare to TDD)

XDD was designed to overcome the limitations of TDD while retaining its key benefits. XDD realizes simultaneous downlink and uplink operation within a TDD carrier by using non-overlapping downlink and uplink frequency resources within the carrier. The allocation of downlink and uplink frequency resources can be done such that it can efficiently handle the asymmetric downlink and uplink traffic ratio of modern day cellular systems. Furthermore, XDD can assign non-overlapping downlink and uplink resources not only in the frequency domain but in the time domain as well. In short, duplexing can be implemented in either time, frequency, or a combination of time and frequency domains within a TDD carrier depending on the needs of the deployment scenario.

In XDD, a base station can schedule non-overlapping frequency resources to terminals so that downlink and uplink transmissions occur even in the same time instance (Fig.3). A cell-edge terminal can be assigned to transmit uplink continuously while the same base station transmits downlink to serve other terminals at the same time. As a result, the accumulated received energy on the uplink at the base station can be larger for XDD compared to TDD to result in an increased coverage. Note that it is only at the base station where simultaneous downlink and uplink operations occurs. For a terminal, it only can transmit uplink or receive downlink at a given time but not both. While supporting simultaneous uplink reception and downlink transmission for a terminal would also have benefits, the necessary implementation burden would be overbearing especially for terminals with small form factors (e.g., smartphones).

Benefit of XDD

One key difference of XDD for a base station is the implementation of self-interference cancellation (SIC) that handles the interference generated by downlink transmission to the uplink reception. With such SIC, an XDD base station could flexibly shift the amount of resources between downlink and uplink not only in time domain but also in frequency domain within a TDD carrier. Following benefits can be expected for XDD compared to conventional TDD:

- Coverage enhancement: The most straight forward way to improve coverage is by increasing the total amount of energy delivered to the receiver. In TDD, the received energy at the base station receiver is limited since only 20%~25% of time resources assigned for uplink in commercial networks. In FDD, this problem would not exist since uplink has full access to all time resources. With XDD, uplink coverage can be extended to be similar to FDD since XDD allows the simultaneous operation of both downlink and uplink within a single TDD carrier. Compared to TDD, XDD uplink can have access to all 100% of time resources.
- Latency reduction: Another drawback of TDD compared to FDD is the latency incurred due to the uplink transmission time not being always available. Because the uplink transmission time is limited, the hybrid automatic repeat request (HARQ) response for the downlink as well as various feedback information carried on the uplink are subject to larger latency when compared to FDD. If the latency of HARQ response for downlink increases, the time required to clear data packets from base station buffers will have to increase as well resulting in a lower user perceived throughput. In XDD, since uplink transmission time can be always available such latency can be easily minimized.
- Throughput enhancement: By extending the uplink transmission time in XDD, it is possible to improve not only coverage and latency but also the throughput. For terminals which are located closer to the center of the cell, the increased uplink resource be used to improve the uplink data rate.

Use cases of XDD

XDD can be applied to various use cases for both access link and backhaul link as follows.

- For 5G macro cells in below 6 GHz: C-band is the most widely deployed spectrum for 5G. Much of these deployments are utilizing carriers located between 3.4 GHz and 4.2 GHz with each operator having access to as much as 100 MHz of bandwidth. All such carriers on C-band are is designated as TDD spectrum. Compared to 5G, 4G was deployed on lower spectrum such as 2 GHz with many of the 4G carriers being FDD spectrum. XDD can be used for 5G macro cells to minimize the impact on coverage due to deployments on higher spectrum.
- For micro cells in millimeter wave (mmWave) band (e.g., 28 and 39 GHz): XDD can also be utilized in mmWave band to improve coverage. Use of mmWave band for cellular networks has been made possible for the first time in 5G. While the use of mmWave band opens up opportunity for realizing data rate in excess of 10 Gbps, the channel conditions of mmWave are very challenging. One key difference between the XDD for below 6 GHz and XDD for mmWave band is how SIC is implemented. For mmWave band, 5G networks rely heavily on multi-beam operation and XDD would have to be implemented to operate concurrently with such multi-beam operation.
- For backhaul and relay links: XDD can also be used for backhaul and relay links. While there have been studies on applying other duplexing technologies such as full duplex (FD) these links, the required implementation complexity is very high. While FD has an advantage over XDD in terms of spectral efficiency, XDD presents a much simpler alternative that can readily address real deployment issues as interference from neighboring operators.

Challenges in XDD

To realize the benefits of XDD in a commercial network, various challenges such as SIC within a base station, management of CLI within the TDD carrier on which XDD is operating, and CLI from adjacent carriers need to be addressed.

Self-interference handling

XDD operation requires advanced SIC implementation at the base station to handle self-interference (Fig. 4). The SIC operates when the base station needs to receive uplink in the same TDD carrier on which it is transmitting downlink (i.e., when the base station is operating XDD). The following requirements need to be met for the SIC implementation of an XDD base station.

- The power of the downlink signal received on the uplink receiver should be sufficiently suppressed to prevent analog-to-digital converter (ADC) saturation.
- Residual interference after SIC must not rise above the base station receiver's noise level to provide sufficient demodulation and decoding performance.
- Frequency separation between the uplink and downlink within the TDD carrier which acts as a guardband should be minimized to achieve XDD without sacrificing resource efficiency.

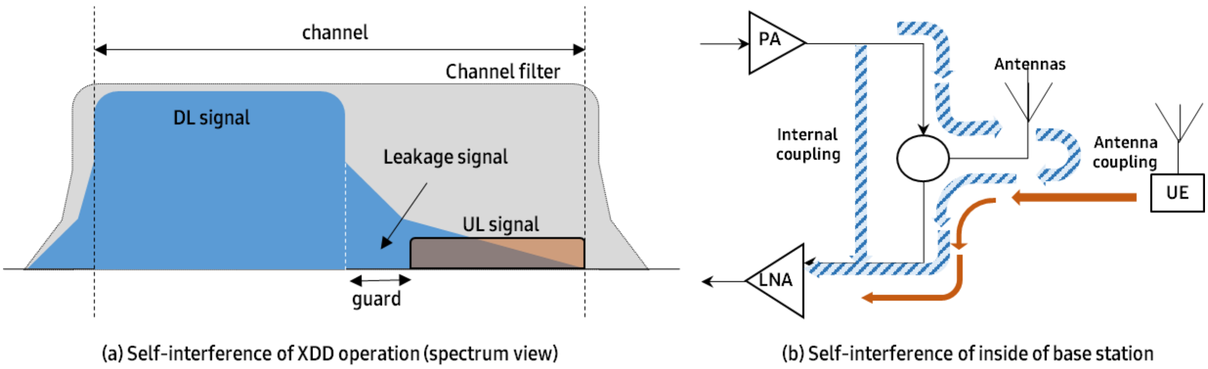


Fig. 4 Self-interference scenario in XDD

Cross-link interference handling

By using XDD at the base station, the uplink and downlink signals are received and transmitted at the same time within a TDD carrier. In an ideal world, XDD's benefits would be achievable by simply implementing capable SIC at the base station. The SIC would handle any downlink interference that might impact the uplink receiver performance. However, in real deployment scenarios, there are other issues to address. Since the terminal transmitting uplink and the terminal receiving downlink are different in XDD, there is a possibility of co-channel CLI among these two terminal. Basically, the terminal transmitting uplink would generate interference to a nearby terminal receiving downlink on the same time resource. Implementing CLI cancellation on terminals would be excessively complex and therefore, it would be up to the base station to schedule terminals which might cause co-channel cross link interference to each other when operating XDD.

Another issue is the handling of adjacent channel CLI, called inter-operator cross-carrier CLI. In many cellular band allocations, one operator's spectrum is located right next to the spectrum of another operator. For example, in one region of the world, which now has nationwide 5G coverage, three Mobile Network Operators (MNOs) are allocated 5G spectrum as follows (also see in Fig.5).

- MNO #1: 3.42 GHz - 3.5 GHz (3GPP band n78)
- MNO #2: 3.5 GHz - 3.6 GHz (3GPP band n78)
- MNO #3: 3.6 GHz - 3.7 GHz (3GPP band n78)

Assume that MNO#2 is deploying XDD in its networks. In such a case, it would have to handle not only the co-channel CLI (e.g., inter-base station and inter-terminal CLI) within its own spectrum but also the adjacent channel CLI generated by the other two MNOs due to insufficient filtering on the downlink transmission. In a conventional TDD system, such an adjacent channel CLI would not be problematic since all three operators would be using the same uplink-DL time resource configuration. In short, there would not be any adjacent channel CLI to begin. Note that handling adjacent channel CLI is much more difficult compared to that of self-interference since *a priori* knowledge on the interference in not available.

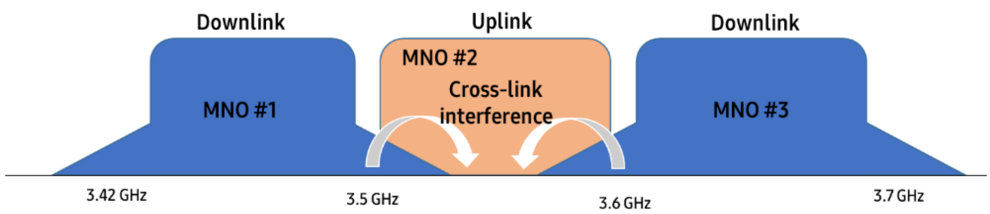


Fig. 5 CLI from adjacent carriers from multi-operator scenario

Technologies for XDD

Self-interference Cancellation

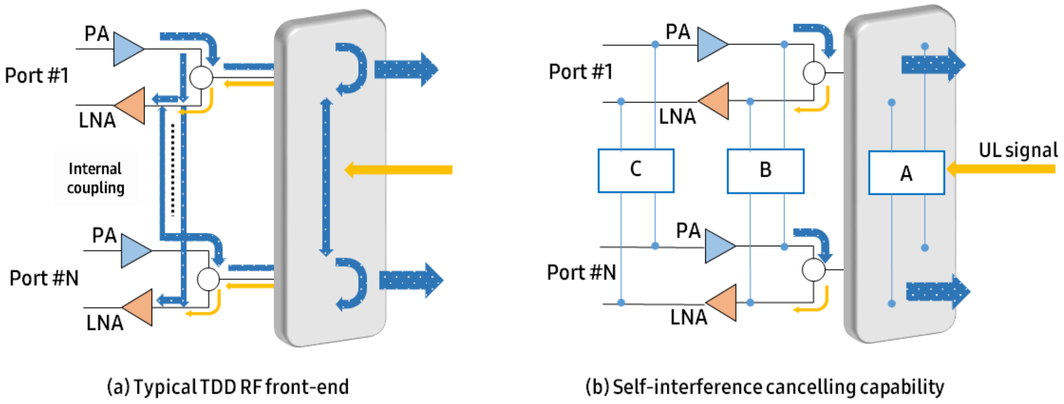


Fig. 6 Self-interference cancellation

Achieving sufficient level of SIC is the most critical part of implementing XDD. Without adequate SIC, the interference from the transmitted downlink signal would corrupt the received uplink signal beyond recovery. For XDD, SIC can be applied in antenna domain, radio frequency (RF) domain, digital domain, or a combination of multiple domains. The characteristics implementing SIC in each domain is summarized as follows:

- Antenna SIC: In order to mitigate the self-interference in the antenna domain, different antennas are used for downlink transmission and uplink transmission in a base station. In such a setup, there are two factors that affect self-interference between the transmit antennas and the receive antennas when they are activated simultaneous in XDD. One is the coupling that occurs in the near-field of the antenna, and the other is the surface wave flowing from the antenna circuit or device. To mitigate self-interference in the antenna domain, the transmit antennas and receive antennas can be isolated by physical distance or by a physical structure which is denoted "A" in Fig. 6.
- RF SIC: Between the transmitted downlink signal and the received uplink signal, the RF signal strength of the downlink signal is much higher at the base station since the uplink signal is subject to a large path-loss whereas the downlink signal is not. Furthermore, the downlink signal is transmitted with an RF chain that can handle much higher transmit power than that of an uplink signal. In order to cancel the high power downlink interference on the received signal, two SIC methods can be considered for the RF domain (denoted "B" in Fig. 6). One method is to utilize passive devices such as a high-performance circulator or duplexer while another method is to use adaptive RF filtering for mitigating downlink interference from uplink signal. A downside of both methods is that cancellation performance is poor if the relative difference in the power of the downlink interference and uplink signal is large. Also, the relevant complexity scales as a function of the number of RF signal paths (i.e., very high complexity for massive MIMO).
- Digital SIC: In order to handle self-interference in the digital domain (denoted "C" in Fig. 6), the downlink interference must be sufficiently mitigated at the antenna or RF stage. Otherwise, the downlink interference will saturate the receiver's ADC making uplink signal recovery impossible. If ADC saturation can be avoided, it becomes feasible for the base station can cancel out the downlink interference. The base station first reconstructs the downlink interference based on its knowledge of the transmitted downlink signal and the coupling channel between the downlink and

uplink RF chains. This reconstructed downlink interference is subtracted from the received signal after ADC. Note that if the downlink interference can be lowered to the noise floor with only antenna and RF domain cancellation, the digital domain SIC is not necessary.

Time and frequency domain resource handling

In the case of conventional TDD, base station uses one TDD configuration (i.e., time resource assignment for downlink and uplink) to operate all terminals in a cell. When dynamic TDD is used, the TDD configuration for each terminal can be dynamically signaled by the base station. Similar to TDD, XDD can be operated in a semi-static manner as well as a dynamic manner. When XDD is operated in a semi-static manner, the base station may allocated to different TDD configurations to regions of its coverage area. An uplink heavy TDD configuration would be assigned to terminals located at the cell boundary while a downlink heavy TDD configuration would be assigned to terminals located near cell center. From a terminal's point of view, it is still operating in a manner that is same as TDD. However, from a base station's point view, it has to handle simultaneous downlink and uplink operation. This method is effective in terms of extending the coverage of uplink while maintaining high downlink throughput for terminals near the cell center. When XDD is operated in a dynamic manner, the base station would have additional flexibility to dynamically fine tune the time and frequency resource assignment of each terminal considering the most up to date information on channel condition, interference level, buffer status, and data priority.

Measurement to estimate cross-link interference

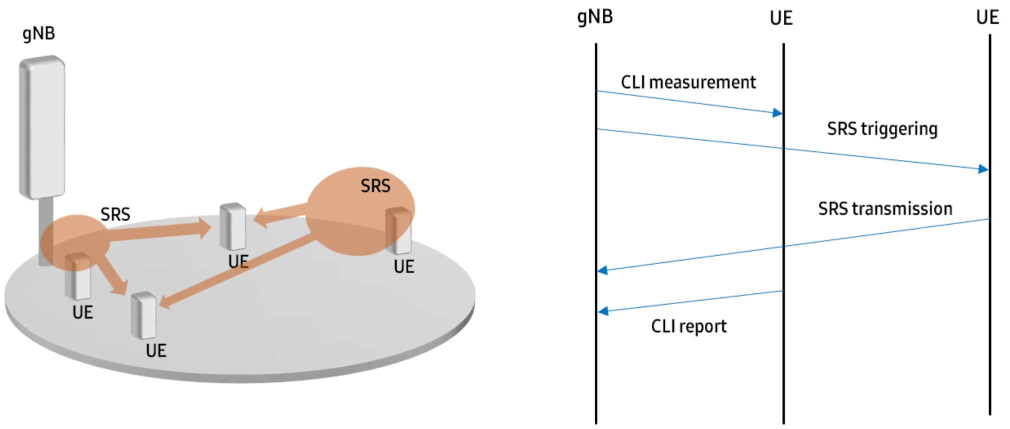


Fig. 8 CLI measurement mechanism

In order to operate XDD, besides the self-interference issue within a base station, the co-channel CLI among the terminals connected the same base station needs to be handled. Among the terminals connected to the same base station, one terminal could be transmitting uplink while another terminal is receiving downlink. If the terminal transmitting uplink is in close proximity of the terminal receiving downlink, the uplink signal could cause interference on the downlink reception despite the low uplink transmission power level. To avoid such a scenario, an XDD base station needs information on radio distance between terminals so that two terminals too close to each other are not simultaneously assigned uplink and downlink.

In Rel-16 NR, as part of enhancing dynamic TDD operation, 3GPP introduced the support for a terminal to measure and report the uplink transmission of other terminals in adjacent cells. For example, in the as shown in Fig. 8, the base station would configure a terminal to measure the sounding reference signal (SRS) transmission of one or more terminals. The measurement would be reported to the base station which would be able to estimate the radio distance between the terminal that took the measurement and the terminals which transmitted SRS. However, this feature relies on a relatively slow feedback mechanism using layer-3 (L3) signaling. Although this feature can be used for XDD as well, a much more accurate mechanism relying on L1 or L2 signaling is expected to provide more benefit for XDD.

Link gain using extended uplink time resources

As described above, the increased uplink time resources in XDD can be used for various purposes. Among them, when used for the purpose of increasing uplink coverage, a terminal may repeatedly transmit uplink data on the extended uplink time resources. Compared to conventional TDD which uses a downlink and uplink time resource ratio of 4:1, XDD would allow the base station use all time resources for uplink as well as downlink. In short, XDD would allow the base station to increase the accumulated uplink received energy to 5 times that of TDD.

To verify the coverage extension performance with XDD, link-level simulation has been performed. The carrier frequency and subcarrier spacing are assumed as 3.5 GHz and 30 kHz, respectively. To consider the coverage limited environments of cell-edge terminals, the number of allocated resource blocks (RBs) and the corresponding occupied channel bandwidth was assumed as 4 RB. Other parameters for the link simulation are shown in Table 1. For TDD uplink, a packet is transmitted once while the same packet is transmitted 5 times for XDD uplink. For repetitive transmission of XDD, incremental redundancy (IR) based HARQ is applied. From the results, it can be observed that an SNR gain of more than 7 dB is achieved by using XDD instead of TDD.

Based on the link evaluation results, the link budget of XDD and TDD can be summarized in Table 2. The residual self-interference assumption of less than 1 is a value after applying multiple SIC schemes observed from actual implementation. At the terminal side, the actual radiated power from the transmit antenna (c) is the sum of transmission power (a) and the effective terminal TX gain (b). At the receiver (i.e., base station) side, the effective noise power (f) can be obtained as the sum of thermal noise power and the effective noise and interference power for the data channel. The thermal noise power can be calculated by the multiplication of thermal noise density (d) and the occupied channel bandwidth (e.g., 4 resource blocks in the NR system). Residual interference after SIC is added in (e) for XDD. Then, two different required signal-to-interference ratios (SINRs) for TDD and XDD to satisfy the target block error rate (BLER) (g) for the given transmission bit rate are applied. Therefore, the receiver sensitivity (h) can be calculated by the sum of effective noise power (f) and the required SINR (g). Taking into account the effective base station antenna gain (i) and channel fading margin (j) properly, the hardware link budget margin (k) for each duplexing scheme can be calculated ((k)=(c)+(i)-(h)). Finally, available pathloss (n) can be calculated with shadow fading (l) and penetration margin (m), that is , (n) = (k)-(l)-(n).

The analysis shows that the proposed XDD can extend the maximum uplink radio distance by 54% compared with that of TDD. This radio distance improvement is equivalent to a coverage area that is 2.37 times that of TDD. A coverage area extension of 2.37 times means that the area covered by 7 conventional base stations using TDD can be replaced with 3 or 4 base stations using XDD without loss of coverage.

Table. 1 Simulation Parameters

Parameters	Value
Carrier frequency	3.5 GHz
TX antenna height	25 m
Terminal antenna height	1.5 m
Target BLER	10%
Pathloss scenario	Non line-of-sight (NLOS) outdoor-to-indoor (O-to-I)
Terminal speed	3 km/h
Number of terminal antenna elements	2
Number of terminal antenna ports	2
Number of base station antenna elements	128
Number of base station antenna ports	2
Subcarrier spacing	30 kHz
Allocated PRBs	4 RB
Channel structure and modulation scheme	Physical uplink shared channel (PUSCH) with QPSK

Table. 2 Link coverage comparison: TDD vs. XDD

Quantity (unit)	TDD (DL:UL=4:1)	XDD
(a) Transmission power (dBm)	23	23
(b) TX gain (dB)	-1	-1
(c) Radiated power (dBm)	22	22
(d) Thermal noise density (dBm/Hz)	-174	-174
(e) Effective noise and interference for data channel (dB)	10	11
(f) Effective noise power (dBm)	-102.5	-102.5
(g) Required SNR from LLS (dB)	4.6	-3.0
(h) Receiver sensitivity (dBm)	-96.4	-104.0
(i) RX gain and loss (dB)	26.1	26.1
(j) Channel fading margin (dB)	30.7	30.7
(k) Hardware Margin (dB)	144.4	15.20
(l) Shadow fading margin (dB)	4.48	4.48
(m) Penetration margin (dB)	26.35	26.25
(n) Available pathloss (dB)	107.8	114.4
Maximum radio distance	136	210
Coverage area ratio	1	2.37

- Note: The values in the table are forreference only and does not imply how commercial products will be implemented.

Summary

This paper highlights the concept, benefits, and technologies of XDD for 5G-Advanced NR Rel-18. XDD enables simultaneous operations of uplink and downlink on the same TDD carrier but on different frequency resources and thus extends the uplink coverage area to be more than 2 times that of TDD. With proper implementation of SIC at the base station, XDD could provide performance benefits in terms of uplink coverage, latency, and uplink capacity with reasonable complexity. More details of Samsung's work on XDD can be found here [1]. These demo systems are expected to be completed in 2021 with plans for public demos in 2022.

References

[1] H. Ji et al., "Extending 5G TDD Coverage with XDD: Cross Division Duplex," in IEEE Access, doi: 10.1109/ACCESS.2021.3068977.