Most LTE networks rely on Frequency Division Duplex (FDD), but with growing numbers of 5G networks being built, Time Division Duplex (TDD) is becoming increasingly important. TDD presents new challenges in network synchronization and coordination between operators because uplink and downlink channels use the same frequency.

This White Paper looks at the techniques for this synchronization and how CSPs can avoid potential interference between base stations and end-users’ mobile devices.
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Executive summary

Although most LTE networks across the globe use Frequency Division Duplex (FDD) technology, the importance of Time Division Duplex (TDD) is growing as it is being used by the first 5G networks. TDD technology brings additional requirements for deployments in terms of network synchronization and coordination between operators. This paper addresses the requirements and the solutions needed in TDD networks. The information can be used by the mobile operators deploying the networks and by the regulators defining the rules of deployment.

While FDD networks have downlink and uplink channels on separate frequencies relatively far apart and well outside the band pass filters of each other, in TDD networks they are located on the same frequency. Also, in the case of adjacent frequencies, uplink and downlink frequencies are typically within the bandpass of each other's filters. Downlink and uplink resources are multiplexed in the time domain rather than in the frequency domain - band pass filters cannot provide the protection from downlink to uplink interference as they do in FDD networks.

As base station (BTS) antennas are typically located on roof tops, there is a good chance for Line of Sight (LoS) between various other BTS antennas and pathloss between antennas is expected to be very small. As the transmission and reception takes place within the band pass of each other's filters, a downlink transmission occurring at the same time as the neighboring BTS reception would cause very severe BTS to BTS interference. For the above reasons, downlink and uplink need to take place simultaneously in all base stations and switching should take place very accurately at the same time. Therefore, TDD networks have strict requirements for synchronization and the timing alignment of downlink and uplink signals for all networks operating on the same band.

TDD base station synchronization can be obtained from GPS or via a transport network with a Timing of Packet (ToP) solution. All operators need to synchronize their networks and use the same TDD frame configuration between uplink and downlink.

Nokia has been involved in delivering, operating and optimizing TDD LTE networks globally for nearly 10 years and has a vast amount of experience in this area.
Interference Scenarios in TDD System

The main interference scenarios in TDD networks are the BTS to BTS interference and UE to UE interference. Both can occur if base stations are not properly synchronized to the same clock source or if different asymmetry is used between downlink and uplink. Figure 1 illustrates both interference cases when Cell 1 and Cell 2 are not synchronized. In the interference case A, Cell 2 transmission to UE2 overlaps with the reception of Cell 1 from UE1. If the two BTSs are close enough, the interference level can be so high that the uplink of Cell 1 is completely blocked by the simultaneous Cell 2 transmission. Interference between base stations is present constantly and is also quite likely.

In the interference case B, UE1 transmission interferes with UE2 reception and if UE1 and UE2 are close enough, the reception of UE2 is blocked by UE1’s transmission. UE to UE interference depends heavily on their locations and on the UE transmission power levels. The worst-case interference can be challenging but the probability is very low because it requires that two UEs from different cells happen to be close to each other and using high transmission power. BTS to BTS interference is typically more challenging than UE to UE interference because there is much more BTS transmission activity, BTS transmission power is high and BTS antennas are located at elevated positions.

Figure 1. BTS to BTS and UE to UE interference
Frame Configuration Options

5G specifications allow many options for splitting the frame between uplink and downlink: the TDD frame size (TDD periodicity) can be selected and the split between downlink and uplink can be selected. The following configurations in Table 1 are expected for the practical cases in 3GPP. All configurations are dominated by the downlink, since the traffic is mainly in the downlink direction. Sub-6 GHz cases use 15 kHz and 30 kHz sub-carrier spacings. The 15 kHz case is aligned with TD-LTE Configuration #2 for those cases where TD-LTE and 5G are deployed in the same band. The 30 kHz case typically uses 2.5 ms or 5 ms switching periods. The co-existence of TD-LTE and 5G in the same band requires the same TDD configuration and the same TDD frame length but not the same sub-carrier spacing. A similar split between the downlink and uplink is also used also for millimeter wave cases. The frame size and the switching period is shorter because sub-carrier spacing of 120 kHz is used. Larger sub-carrier spacing and a shorter TDD frame also produces a lower latency.

Table 1. Example TDD frame configurations

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<th>1ms</th>
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<tr>
<td>15 kHz 5 ms</td>
<td>D S</td>
<td>D S</td>
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<tr>
<td>30 kHz 5 ms</td>
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<td>30 kHz 5 ms</td>
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<td>30 kHz 2.5 ms</td>
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<tr>
<td>30 kHz 2 ms</td>
<td>D D</td>
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<tr>
<td>120 kHz 0.625 ms</td>
<td>D D</td>
<td>D S</td>
<td>U</td>
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</tr>
<tr>
<td>120 kHz 0.5 ms</td>
<td>D S</td>
<td>U</td>
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<tr>
<td>120 kHz 0.5 ms</td>
<td>D D</td>
<td>S</td>
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</tbody>
</table>

D = Downlink  
S = Switching  
U = Uplink

Switching slot includes downlink + guard period + uplink

Cell Size and Frame Configurations

TDD frame configurations affects the relative capacity split between downlink and uplink, the latency, and also the maximum cell radius. If we have just one uplink slot in the frame, only a short PRACH can be used, limiting the cell radius. For example, the maximum cell radius with a short PRACH with a 30 kHz subcarrier spacing is less than 5 km, and with 15 kHz subcarrier spacing less than 10 km. A larger cell radius may be needed, particularly in suburban and rural cases where high base station antennas and open propagation can enable larger cells offering greater propagation. A long PRACH allows very large cell sizes. It is possible with two consecutive uplink slots, for example, with the DDDSUDDSUU frame shown in Figure 2.
Guard Period and Safety Zone

The duration of the Guard Period (GP), measured in microseconds, defines the interference safety zone distance. GP is needed for switching between downlink and uplink and for avoiding interference between downlink and uplink. The safety zone refers to the distance between TDD transmitter and receiver where the interference can be avoided through the guard periods. If we go beyond the safety zone and the interference happens to propagate far enough, there may be interference between downlink and uplink.

At the speed of light, in one microsecond the radio waves travel 300 m. To achieve, for example, a 15 km safety range, about 50 µs GP would be required, from when the transmitter switches off to when the receiver is switched on. Should those two sites be located 15 km apart, with a line of sight between the antennas, path loss would be 127dB and interference potentially still over 50 dB above thermal noise. If a 40 km safety zone is required, 134 µs GP would be necessary – but this also emphasizes the requirement for good quality physical layer design and the importance of reducing overshooting.

5G slot formats defined in 3GPP specification 38.211 (table 4.3.2-3) can contain a certain amount of guard symbols defined by the BTS. Typical settings for guard symbols are two or four in the case of 30 kHz sub-carrier spacing. Calculation of the safety distance should also consider factors such as the transit period for switching off the transmitter, which reduces the practical safety range. These are included in the following picture showing the safety zone ranges for different GP configurations.

Figure 2. Frame configurations with 30 kHz subcarrier spacings and PRACH options

Figure 3. Safety zone ranges with different GP configurations
Having a greater GP allows for greater safety zones and helps cope with small timing alignment errors, yet comes at the cost of capacity and peak throughput. For example, five guard symbols with 30 kHz provides a 50 km safety zone but takes about seven percent of capacity with a 2.5 ms frame size. The GP should be defined such that downlink and uplink do not overlap at all, including the last symbols, since 5G with low latency targets does not use block interleaving for interference averaging.

**Interference Distance**

As there is often a line of sight between BTS antennas located on roof tops, the RF path between BTS sites provides very little isolation. Hence BTS to BTS interference can be considered as the worst kind of interference that can occur in a TDD network. Calculations in Figure 4 show the increase in dB to the noise floor and assume a worst case scenario where transmitting and receiving antenna are pointing towards each other and there is no obstruction between them.

**Figure 4. Intra-frequency BTS to BTS interference**

![Intra-frequency interference](image)

The above figure shows that the potential interference over the thermal noise in the victim cell receiver would be a massive 40 dB as far as 50 km away. This is clearly unwanted, and it is obvious that BTSs on the same frequency are required to switch to transmit and receive simultaneously.

BTS to BTS interference can also occur between two operators on adjacent frequencies. The frequency domain filtering can attenuate the interference by 40-45 dB between adjacent frequencies, but it is not enough to completely avoid interference. The potential inter-frequency interference can happen several kilometres away as shown in Figure 5. In many cases, operators share BTS sites and the isolation between antennas is less than 60 dB. These calculations indicate that adjacent operators need to synchronize their TDD networks and use the same asymmetry configurations.
A receiver’s ability to decode a wanted weak signal at its assigned channel when a strong signal is present on an adjacent channel is also an important factor to consider. This receiver performance is also specified by 3GPP. Figure 6 shows the power above adjacent channel selectivity (ACS) requirement as a function of coupling loss and distance.

Antenna down tilting is generally used in BTS antennas to minimize inter-cell interference. The down tilting also helps also to minimize the interference distance between downlink and uplink transmissions.

A relatively rare mode of radio propagation which is often referred to as atmospheric ducting is also worth mentioning. During certain weather conditions, such as inversion layers, the radio waves are bent between different horizontal atmospheric layers of different densities, forming a waveguide. This can result in a radio channel in which the radio waves can follow the curvature of the Earth and have a much-reduced attenuation. Due to the reduced attenuation, interference can be occasionally experienced even hundreds of kilometres away. Some geographical areas are more likely to experience such conditions than others.
Synchronization Requirements in 3GPP

3GPP TS38.133 section 7.4 defines Cell phase synchronization accuracy for TDD as the maximum absolute deviation in frame start timing between any pair of cells on the same frequency that have overlapping coverage areas. The minimum requirements of the cell phase synchronization accuracy measured at BTS antenna connectors is defined as better than 3 µs. The cell phase synchronization accuracy was defined based on the different UL/DL interference scenarios mentioned earlier where several important factors such as cell size, timing advance, BTS switching time, UE switching time and the GP duration were taken into consideration. The value of 3 µs is applicable for all sub-carrier spacings defined in 3GPP Release 15, i.e. 15 kHz, 30 kHz, 60 kHz and 120 kHz. It is important to note that due to short symbol duration of 60 kHz and 120 kHz sub-carrier spacing, a minimum of two GP symbols are required to avoid UL/DL interference. The phase synchronization requirement has been true already for all TD-LTE networks and will also apply to 5G TDD networks.

Synchronization Sources

Global Navigation Satellite System (GNSS)

GNSS is a general term describing any satellite constellation that provides positioning, navigation and timing services on a global basis. It is probably the most accurate timing system that is both available globally and affordable by telecom operators (compared to, for example, a Rubidium clock). GNSS available today are:

- GPS is operated by the US military and is the most popular GNSS system worldwide
- GLONASS is a global GNSS owned and operated by the Russian Federation.
- Beidou is a regional GNSS owned and operated by the People’s Republic of China. China is currently expanding the system to provide global coverage by 2020
- Galileo is a global GNSS owned and operated by the European Union. The system is planned to be completed by 2020.
- QZSS is a regional GNSS owned by the Government of Japan and operated by QZS system service Inc. (QSS). Japan plans to have an operational constellation of four satellites by 2018 and to expand it to seven satellites by 2023.

GNSS solutions involve connecting the GNSS antenna/receiver to the Base Station. The GNSS receiver is a device that receives and digitally processes the signals from a GNSS satellite constellation to provide position and accurate time information to the BTS. The GNSS receiver can be a single device that integrates both antenna and receiver or it can be separate from the antenna. In the latter case, the GNSS receiver is connected to the antenna by coaxial cable and provides the power directly to the antenna. Nokia offers both solutions to customers to meet all their deployment scenarios. The GNSS receiver traditionally needed clear satellite visibility. The high sensitivity of the Nokia receiver combined with multipath and signal reflection mitigation algorithms makes it possible to operate in more challenging environments, including urban canyons. When operating with reflected GNSS signals, our receiver employs a location survey algorithm that minimizes the error in timing and position that may otherwise be present. The GNSS receiver is then directly connected to the synchronization Input interface of the BTS. DC power for the GNSS receiver is supported through the combined power and control cable connected to the Sync Input interface of the BTS. The BTS provides an integrated power feeding to the GNSS receiver, enabling maximum cable lengths of 300 m.
The deployment of a GNSS receiver can prove difficult because it often requires clear satellite visibility, although new, more robust GNSS receiver designs are becoming available. This means that GNSS receivers may not be installable in locations such as inside buildings, urban canyons or tunnel where clear satellite visibility will be an issue. The accuracy and stability of GNSS solutions may be affected by factors that are outside operators’ control, such as bad weather conditions, jamming or spoofing. Therefore, an alternative solution for synchronization is Timing over Packet.

**Timing over Packet (ToP)**

Timing over Packet (ToP) with phase synchronization is a solution where phase synchronization can be obtained from the transmission network or backhaul network of the BTS and can meet the requirements mentioned. Nokia ToP with Phase synchronization solution is based on the IEEE1588-2008 standard and follows the ITU-T profile.

The relationship between IEEE1588-2008 and ITU-T deserves some explanation as this is often misunderstood. IEEE1588-2008 is a standard which defines a set of methods and attributes to be used to achieve timing accuracy in a packet network. It is not designed specifically for any applications. It can also be used in industry for automation purposes. For IEEE1588-2008 to be usable in a real-life network, the standard requires that a “profile” shall be created to meet the requirement of each application. ITU-T, which is a telecommunication standardization body, then takes the IEEE1588-2008 standard and defines a set of profiles to be used for telecommunication purpose. There are some telecom vendors that do not support ITU-T profiles and use their proprietary profile, claiming compliance with IEEE1588-2008. Such equipment may have interoperability issues with equipment that supports ITU-T telecom profiles. Operators should therefore strictly follow ITU-T profiles for deployment of ToP with phase sync solutions.
Apart from the set of functionalities defined in ITU-T that shall be implemented in network elements such as BTSs, transmission equipment and Grandmaster, ITU-T also defines network recommendations for phase synchronization deployment which operators can follow to ensure successful deployment of ToP with Phase synchronization.

Figure 8. ToP with Phase synchronization solution

Conclusions for Regulators

As many operators and countries are expected to join the TDD technology through 5G, the government frequency regulators are in a good position to make 5G an attractive, affordable and successful choice for mobile network operators. Nokia would recommend regulators to consider the following:

- 3GPP defines the emission masks and all mobile device and BTS vendors must comply. It would be beneficial for the regulators to follow the 3GPP masks.
- Regulators should allocate the whole band to TDD, since combining TDD and FDD networks in the same band would generate interference issues.
- All mobile network operators operating on the same TDD band should be phase synchronized, aligned and all operators should have the same or a compatible UL:DL frame ratio. This is commonly established practice in countries where TD-LTE is in use. There may also be a need to agree a UL:DL split between neighboring countries.
- Selection of TDD frame configuration should consider the maximum cell radius. Two consecutive uplink slots are required to support a cell radius of more than 5-10 kilometres.
- Nokia recommends that the regulators let mobile operators to select and agree on the frame configuration. Only in case it cannot be agreed, regulator should enforce it.
- The main source of synchronization should be GPS or Timing over Packet in the latter case it can be guaranteed that all the routers in the network support border clock functionality.
- Technologies not able to comply should not be allowed in the same band.
- Even if BTSs were equipped with additional (and expensive) filters to mitigate some of the issues, severe UE to UE and BTS to BTS interference cannot be avoided.
- New technologies and future releases of the 3GPP specifications may potentially improve the situation by enabling dynamic TDD, at least in local deployments.
3GPP References

3GPP TS 36.101 V15.2.0, User Equipment (UE) radio transmission and reception
3GPP TS 36.104 V15.2.0, Base Station (BS) radio transmission and reception
3GPP TS 38.101-1 V15.1.0, User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone
3GPP TS 38.101-2 V15.1.0, User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone
3GPP TS 38.104 V15.1.0, Base Station (BS) radio transmission and reception
3GPP TS 36.211 V15.1.0, Physical channels and modulation
3GPP TS 38.211 V15.1.0, Physical channels and modulation

Abbreviations

AAS    Active Antenna System
ACLR   Adjacent Channel Leakage Radio
ACS    Adjacent Channel Selectivity
BBU    Baseband Unit
BTS    Base Station
CDMA   Code Division Multiple Access
CPRI   Common Public Radio Interface
DL     Downlink
dMIMO  Distributed MIMO
DTDD   Dynamic TDD
eCPRI  Evolved CPRI
eMBB   Enhanced Mobile Broadband
EMF    Electromagnetic Field
EN-DC  E-UTRAN – New Radio Dual Connectivity
FDD    Frequency Division Duplex
GNSS   Global Navigation Satellite System
GP     Guard Period
GPON   Gigabit Passive Optical Network
GPS    Global Positioning System
IoT    Internet of Things
LTE    Long Term Evolution
MBB   Mobile Broadband
MIMO Multiple Input Multiple Output
MRDT Maximum Receive Timing Difference
NR   New Radio
mMIMO Massive MIMO
PRACH Physical Random-Access Channel
PTP   Precision Timing Packet
RF   Radio Frequency
RRU Remote Radio Unit
SSF   Special Subframe
STDD Static TDD
TDD   Time Division Duplex
ToP   Timing over Packet
TRX Transceiver
TTI Transmission Time Interval
UE   User Equipment
UL   Uplink

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