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Much has been done to accurately measure the time error associated with network equipment, however, measuring the time error of a 5G NR or 4G LTE base station with no 1pps output is a challenging problem. One option is to make a measurement of the downlink radio signal.

This primer describes how to make such an over-the-air “time error” measurement by decoding and examining the synchronization signals and comparing them to an external time reference.

Making Over-the-Air SYNC MEASUREMENTS

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Introduction to 4G LTE Downlink Radio Frame Timing

The LTE radio downlink is an OFDMA (Orthogonal Frequency Division Multiple Access) signal – which means that it uses both Frequency and Time Division multiplexing to share resources between users. Full details can be found in the 3GPP specifications or in other publications.

In the time domain, the transmission consists of 10ms frames. Each frame is divided into 10 subframes. Each subframe is further divided into 2 timeslots, each of which contains 6, or more usually 7 symbols. Each symbol also contains a cyclic prefix, (to cope with multipath effects) resulting in a useful symbol length of 66.7us.

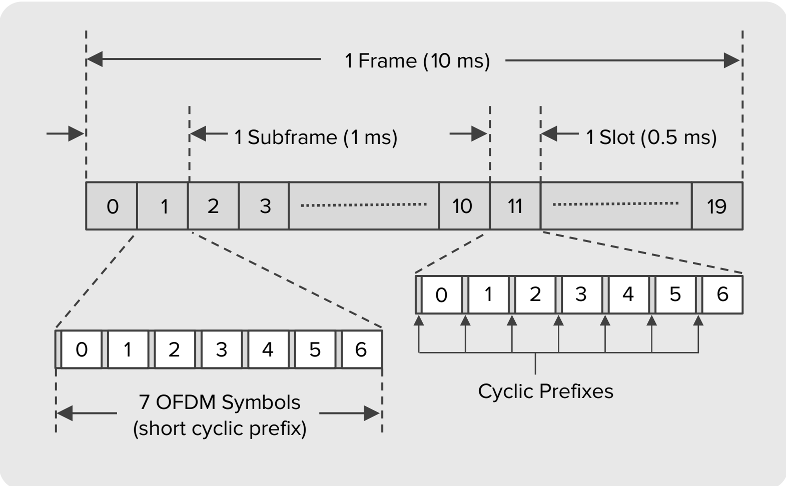

Figure 1. LTE Frame Structure

There are also two duplex schemes for managing uplink and downlink transmissions. These are Frequency Division Duplex (FDD) and Time Division Duplex (TDD). In FDD the uplink and downlink are on different frequencies but are both continuous. In TDD they are on the same frequency and switch between transmit and receive according to a specific schedule.

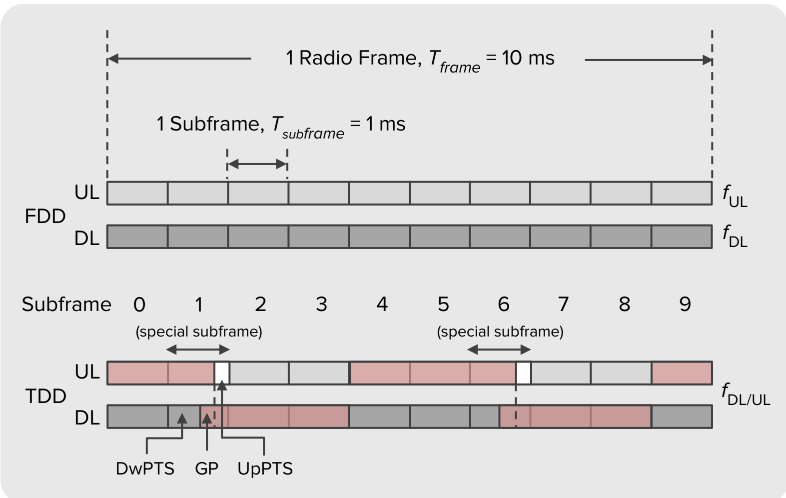

Figure 2. Comparison of FDD and TDD Frame Structures

FDD has typically only required that base stations within the network be syntonised – or frequency aligned, whereas TDD requires that they be phase aligned within 3 us. This is to avoid interference issues. Some features now available within FDD such as eICIC (Enhanced Inter-Cell Interference Coordination) and CoMP (Coordinated multi-point) also require phase alignment. The standards do not describe how this alignment should be achieved. One method – and the one we assume for our measurement – is to start transmission of the first frame from each base station at the top of second. This means that the start of every hundredth frame transmitted will occur at top of second.

Note that it is not possible just by listening to the radio signal to determine where every hundredth frame will occur. The system frame number is modulo 1024, so some assumptions must be made.

The frames transmitted on the downlink contain a mixture of user data, control data and specific signals used for synchronization and measurements. There are two such synchronization signals that are each transmitted twice within a frame. These are the Primary and Secondary Synchronization Signals (PSS and SSS). User Equipment (UEs) synchronize to a base station (Enode-B) by detecting these signals and using them to determine their own timing relative to the base station. This ensures that they receive and transmit at the correct times.

These signals always appear at the same points within the radio frame – although the relative positioning in time varies between FDD and TDD. These signals also encode the physical cell ID – but they do not encode any information about the actual time – they are simply markers. The synchronization signals each occupy a single symbol in time, spread across the central 72 subcarriers.

5G NG Frame Structure

5G NR is similar in many ways to 4G OTA. Both use OFDMA. However, in addition to the other modulation schemes used in 4G, radio conditions allowing, it can use 256-state quadrature amplitude modulation (256QAM).

Like 4G, the frame is 10ms long with 1ms subframes, but it is a lot more flexible but also more complex. There are differences in the frame structure allowing more symbols per frame.

Cell bandwidths up to 100MHz are possible in 5G NR frequency range 1 (FR1) and up to 400Mhz in FR2.

Like with 4G, the PSS and SSS are of particular interest in 5G and it is by detecting these signals that we can determine the synchronization of the overall 5G signal. In 5G the PSS and SSS signals are 127 symbols wide and carry the physical channel ID which in 5G is between 0 and 1007. The PSS and SSS are in what is called the Synchronization Signal Block (SSB). These SSBs are transmitted in bursts with multiple SSBs per burst. By coding each SSB slightly differently, the user equipment can determine which beam it is in and the base station can optimize the transmission.

An additional complication in 5G compared to 4G is the frequency where the synchronization signals are transmitted. In 4G, these are transmitted on the central subcarrier. However, in 5G, sync signals can be positioned on another subcarrier within the cell bandwidth. This makes them harder to find but does lead to less chance of interference from adjacent cells that might be on the same frequency.

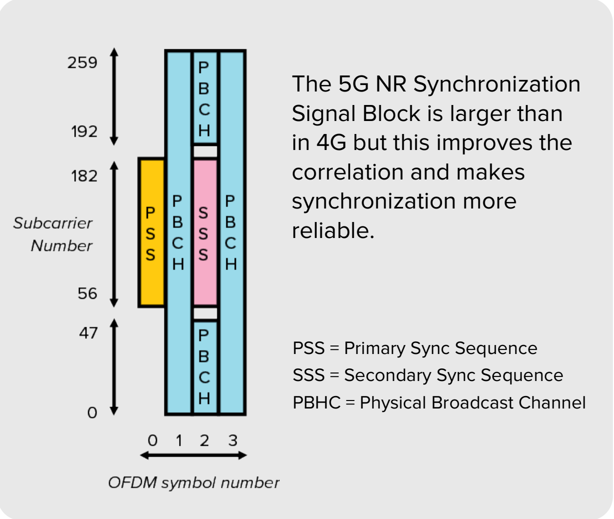

Figure 3. 5G NR SSB structure

Measuring Time Error Over the Air (OTA)

An absolute time error measurement can be made by tuning the receiver to the correct frequency, down-converting, digitizing and demodulating the radio signal and finding the position of the PSS within the radio frame. The absolute time position of the PSS can be determined using an external reference such as GPS. This can then be used to determine the absolute start time of the frame. By assuming that transmission is initiated at top of second as described above and that any error is within a maximum of 10ms, and allowing for time of flight from the antenna and any other delays, it is possible to determine the absolute time error of the base station. Of course, if transmission starts at a known offset from top of second then it is possible to compensate appropriately.

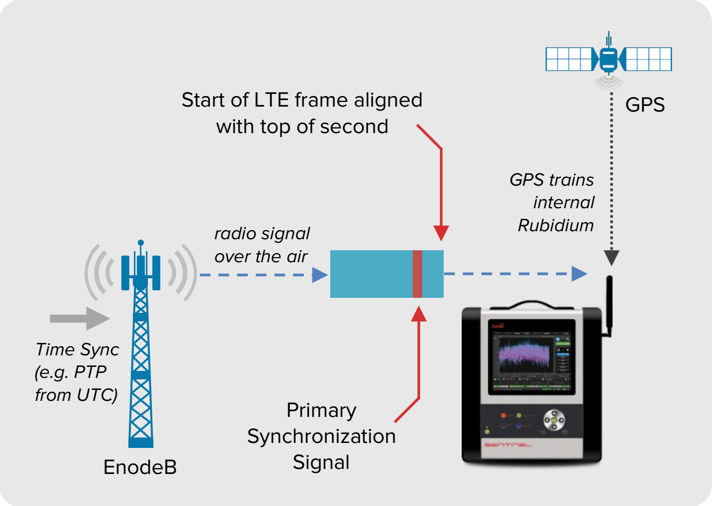

Figure 4. Making a Time Error measurement by using the PSS to determine the start of Frame Time

In practice the technique requires a little more work than this due to the way that the LTE signal is specified. The PSS transmitted in each half of the frame (1 of 3 possible sequences) is the same – but the SSS (1 of 168 possible sequences) differs slightly – allowing determination of which half of the frame has been detected. The relative positioning of the SSS versus the PSS determines whether FDD or TDD is in use.

The accuracy and resolution of the measurement are partly determined by the rate at which the radio signal is sampled, (the higher the rate the better the resolution). Typically, the sample rate for LTE is 30.72 MHz, resulting in a sample time or resolution of approximately 32.5 ns. A higher sampling rate can be used to achieve higher resolution.

To find the absolute time of signal reception it is necessary to timestamp the RF samples as they are gathered. These timestamps are stored along with the samples. The PSS and SSS and their positions are determined by correlating the received samples with ideal signals. The timestamps of the correlated samples can then be used to provide an absolute measurement.

To achieve the best accuracy of the measurement it is necessary to accurately measure the distance from the measuring receiver to the base station and to characterise the delays within the receiver.

Other Applications

As well as measuring the absolute time error of an individual base station, this technique can be extended to make other useful measurements.

Relative Timing Error

As well as making measurements of an individual base station it is possible to measure two base stations in quick succession – and thus determining the relative time error between them. As well as for TDD, this is of particular interest in the case of FDD cells where eICIC is in use – since this requires coordination of downlink power control between cells.

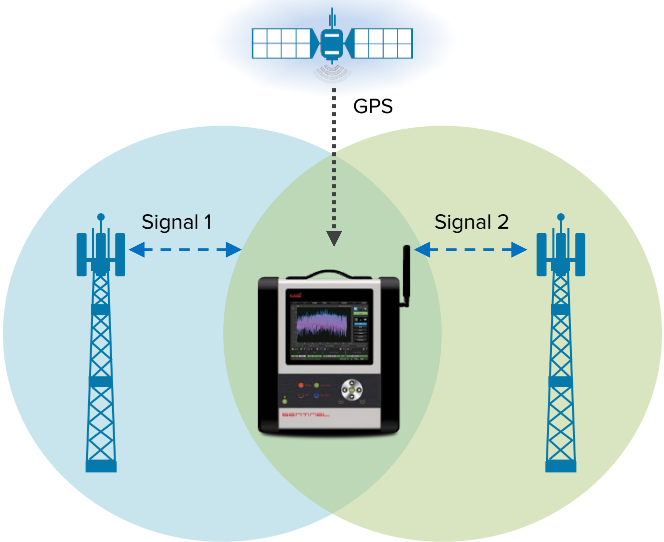

Figure 5. Test set compares timing of Signal 1 and Signal 2 vs GPS (external reference)

For this measurement to work it is necessary to be able to receive the signal from both base stations at a single location and to differentiate between them. This can be challenging as both 5G NR and 4G LTE are single frequency networks, and the PSS and SSS signals are not designed to be interference resistant. (Note – the specific signals will be encoded differently for different base stations.) In practice it will be necessary to be near the inter-cell boundary.

Carrier Aggregation

An additional driver for synchronization is carrier aggregation. Carrier aggregation is one technique allowed for in 5G and is a mechanism to increase the data rate per user.

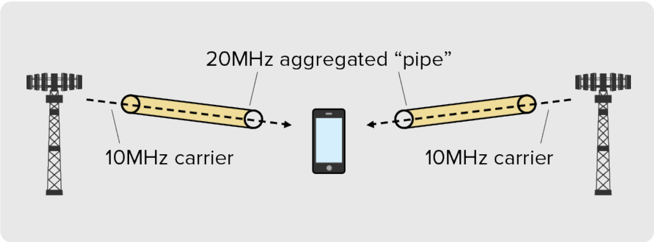

Figure 6. Carrier channels combined into single aggregated channel

Available in both 4G LTE-A and 5G NR, carrier aggregation allows the combination of two or more carrier channels into a single aggregated channel, thus enabling higher throughput and more efficient use of spectrum. However, to make this work, timing alignment error of no greater than 260ns is required.

Observed Time Difference of Arrival (OTDOA)

A scheme is defined for determining position by comparing the relative arrival time of specific signals from 3 (or more) base stations and triangulating. This is designed for use by emergency services for example, to locate an incident. The full application requires the use of a defined protocol to determine when the particular signals are transmitted, and in the case of a UE, to command them to make measurements and return the measurements to the network.

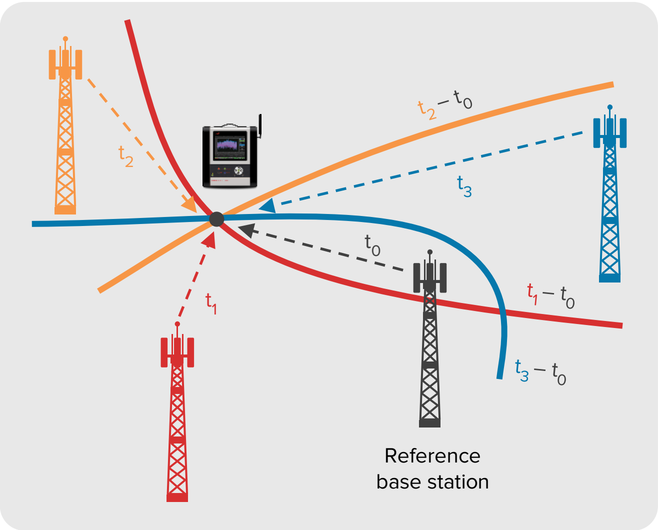

Figure 7. Observed time difference of arrival

For test equipment it is only necessary to know when and where within the downlink structure for each base station, to listen for the particular signals. There is no requirement to return the measurements to the network.

The signals are of a similar form to those used for the SSS. As for the relative timing case above it is necessary to be in a location where signals from all three stations can be received. Because the transmission of these signals is coordinated between the base stations this is potentially easier than receiving and measuring different PSS/SSS combinations.

By making measurements of these signals and comparing them to each other, using the external reference, it is possible to determine the accuracy of the positioning scheme.

MIMO

A significant enhancement in 5G, especially in the FR2 band, is the use of beam forming. In FR1, the RU can use up to 8 beams and in FR2 up to 64. This allows the radio energy to be directed for optimal utilization. This also enables MIMO (Multiple input multiple output) in which beams are optimized to allow reliable communication with multiple users in a potentially reflection rich environment. The ITU-T standards require a time alignment error (TAE) as low as 65ns in some MIMO applications.

Figure 8. MIMO beams are used in reflection rich environments

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