Deriving the phase synchronisation requirement for outdoor long-term evolution small cell enhanced inter-cell interference coordination

Charles Dominique[1], *David Dominique*[2]

[1]*G2 Little Pearls, Cooke Town, Bangalore, India*
[2]*161 Leota Avenue, Sunnyvale, CA, USA*
E-mail: daviddominique2000@gmail.com

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Abstract: This study addresses the phase synchronisation requirement for optimal enhanced inter-cell interference coordination operation for outdoor small cells in a long-term evolution heterogeneous network with a macro overlay.

1 Introduction

Long-term evolution (LTE) is the world's fourth generation wireless cellular telephony standard that is being widely deployed today. In the outdoor environment, small cells in LTE play an important role in improving data throughput performance. This is achieved by deploying small cells under the same coverage area of an overlay macro cell operating on the same set of carrier frequencies. The deployment of small cells under a macro cell's coverage creates inter-cell interference between the macro cell's downlink transmissions and the small cell's transmissions when both use the same carrier frequencies, since both transmissions overlap each other in both time and frequency sub-carrier space. This interference problem is particularly acute for those users [or user equipment (UE)] at the border of the small cell's coverage area. The exact impact of the interference is a function of the macro cell's power (typically much larger than that of the small cell), how far away the small cell is from the macro transmitter as well as the propagation channel characteristics from both the macro and small cell transmitters to a user. This inter-cell interference can cause poor small cell border performance and also limits the deployment flexibility of small cells. Without further enhancement, small cells can only be deployed in places where the macro's transmissions are not strong enough to significantly interfere with the small cell.

To mitigate this interference problem, Release 10 of the LTE standard specified use of a technique known as enhanced inter-cell interference coordination (eICIC) specifically designed to improve the performance of LTE small cells in such heterogeneous network (HetNet) deployments with macro cells when using the same set of carrier frequencies. eICIC [1] coordinates downlink transmissions from a macro cell and a small cell such that these transmissions do not overlap with one another in time as seen in Fig. 1. The macro cell essentially stops or blanks its own downlink packet data shared channel transmissions during certain sub-frames, called almost blank sub-frames (ABSs). This blanking pattern is communicated by the macro cell to all the small cells deployed in its coverage area. The small cells schedule the transmissions to their own cell border users during these ABS time slots. This coordination reduces the amount of inter-cell interference between the macro and the small cell for users at the edge of the small cell coverage area, thereby improving cell edge throughput, coverage and deployment flexibility. The small cell is free to schedule transmissions to its cell centre users using all the sub-frames, since they are much closer to the small cell transmitter and hence are not impacted much by the interference from the macro.

For the coordination to succeed, it is critical that the downlink sub-frame from the macro be properly aligned with the downlink sub-frame from the small cell at the UE as shown in Fig. 2 to ensure that these transmissions do not overlap. When there is a timing mis-alignment, a portion of the macro's sub-frame will overlap with a portion of the small cell's sub-frame resulting in inter-cell interference in the overlap region and is shown in Fig. 2.

eICIC thus requires frequency, time and phase synchronisation between the macro and small cells for optimal operation. Frequency synchronisation is required to ensure that the clocks have the same periodicity. Time (also known as time of day) synchronisation ensures that the macro and small cells are synchronised with regard to sub-frame numbering which is essential to ensure that both the macro and small cell have the same notion of when the ABS periods occur. Phase synchronisation of the macro and small cell clocks is required to ensure that the sub-frame boundaries are time aligned.

The third generation partnership program (3GPP) has defined the frequency synchronisation requirements [2]. 3GPP has however not explicitly defined the phase synchronisation requirement for eICIC outdoor HetNet deployments. Various publications [3] have indicated different values (anywhere from 1 to 5 μs) for what the phase synchronisation needs to be, without a detailed analysis.

This paper determines the worst-case operational scenario that derives the phase synchronisation requirement and derives an expression that can be used to generate the phase synchronisation specification. The analysis shows that the phase mis-alignment of the sub-frames at the UE is due to two components: one due to the clocks being phase mis-aligned and a second component due to differential propagation path delay between the macro cell and small cell transmissions at an UE. The relationship derived here and the analysis of the use cases will enable mobile network operators to more accurately engineer their networks to optimise LTE small cell operation.

2 Determining the worst-case scenario

In a HetNet deployment with both the macro and small cells operating on the same carrier frequencies, for eICIC to be effective, it is important that the downlink signals transmitted out of the macro base station as well as that from the small cell be time aligned at the UEs so that they do not overlap with each other. Otherwise the signals from the macro and the small cell will interfere with each other when received at the UE resulting in degraded throughput. This requires that the sub-frame timing of the downlink LTE transmissions from the macro cell and the small cell be frequency, time and phase aligned as received at the UE.

A difference in the time between the start of the sub-frame in the transmission from the macro and that from the small cell as seen at the UE receiver can occur due to three reasons:

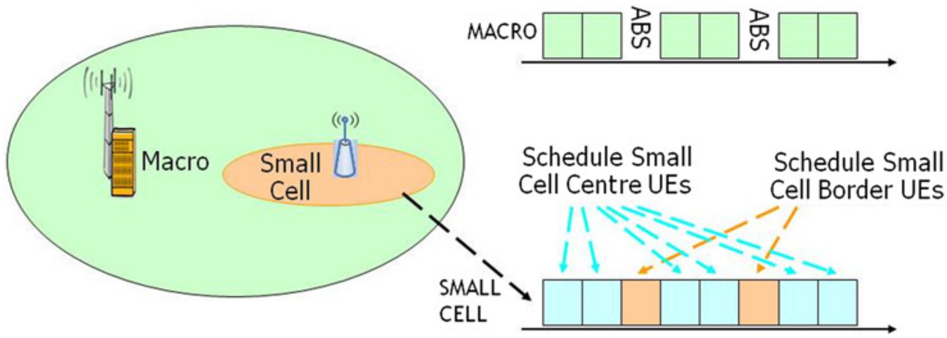

Fig. 1 *eICIC operation in a heterogeneous deployment*

(i) Variation in the periodicity of the clock caused by frequency variation in the clocks.
(ii) Phase difference in the clock used in the macro against the small cell.
(iii) Differential path delay between the macro and the small cell propagation paths to the UE.

For this analysis, we will assume that perfect frequency synchronisation has been achieved and hence the only impact is from items (2) and (3) above.

Phase differences between the phase-locked loops (PLLs) used in the base stations to generate their timing is one source of phase mis-alignment. Even though the macro and small cell base stations use reference clocks that are typically synchronised to global positioning system or to network timing using PLLs, these PLLs have some residual phase error in addition to jitter which creates time-varying drift of the clock.

Since the requirement is that there should be no overlap of the sub-transmitted frames from the macro and small cell as received at the UE location, differences in the propagation path delays in the transmission from the macro compared with that from the small cell to an UE also contribute to the sub-frame mis-alignment at that UE. As can be seen from Fig. 1, the signal transmitted from the macro cell travels a longer distance to the UE of interest compared with the signal from the small cell transmitter. This is because the UE that is attached to the small cell is closer to the small cell than it is to the macro. This differential path delay results in the small cell sub-frame colliding with the macro sub-frame at the UE receiver even if perfect frequency, time and phase synchronisation of the macro and small cell clocks has been achieved.

Two scenarios need to be analysed. In scenario 1, the small cell's sub-frame timing phase is advanced with respect to the macro cell's sub-frame timing when compared at their respective antenna ports. Scenario 2 is the opposite with the small cell's timing delayed relative to the macro.

Fig. 2 shows the timing diagram of scenario 1 where the small cell's sub-frame timing phase is advanced relative to that of the macro. In the following analysis, we will use the macro's timing as the reference and relate all subsequent delays to it. As seen from Fig. 2, the clock phase mis-alignment and propagation delays cause the leading edge of the small cell's $N+1$th sub-frame to overlap with the trailing edge of the macro's Nth transmitted sub-frame. The total overlap time in this scenario can be expressed as

$$T_{\text{overlap}} = T_P + (T_1 - T_2) \tag{1}$$

where T_P is the amount of time by which the small cell sub-frame timing is advanced relative to the macro sub-frame at their respective transmit antenna ports, T_1 represents the propagation delay from the macro to the UE at the small cell border, T_2 represents the propagation delay from the small cell to the UE at the small cell border and $T_1 > T_2$. $(T_1 - T_2) = T_{\text{Diff\_Prop\_Delay\_Time}}$ represents the differential propagation delay time.

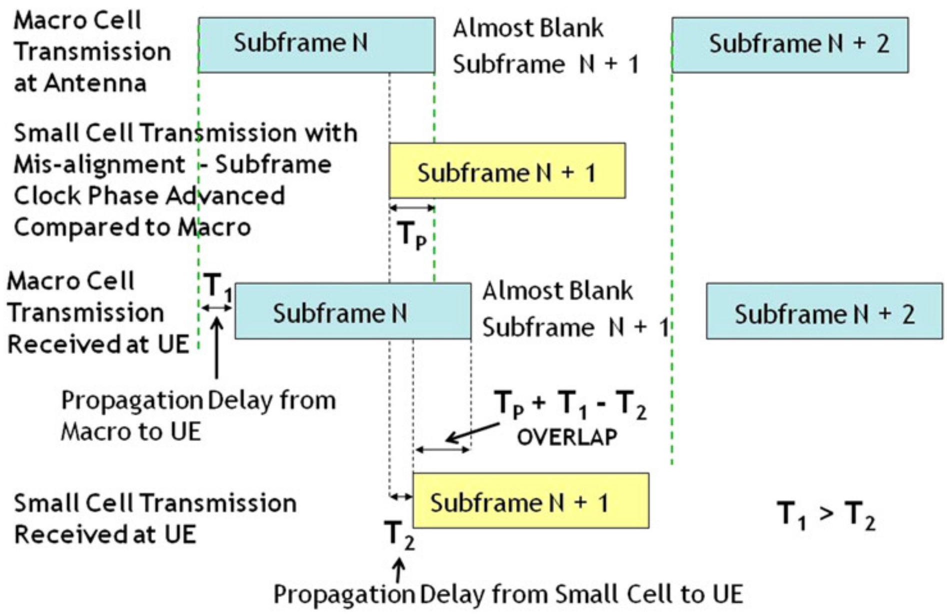

Fig. 2 *Impact of phase mis-alignment for scenario 1*

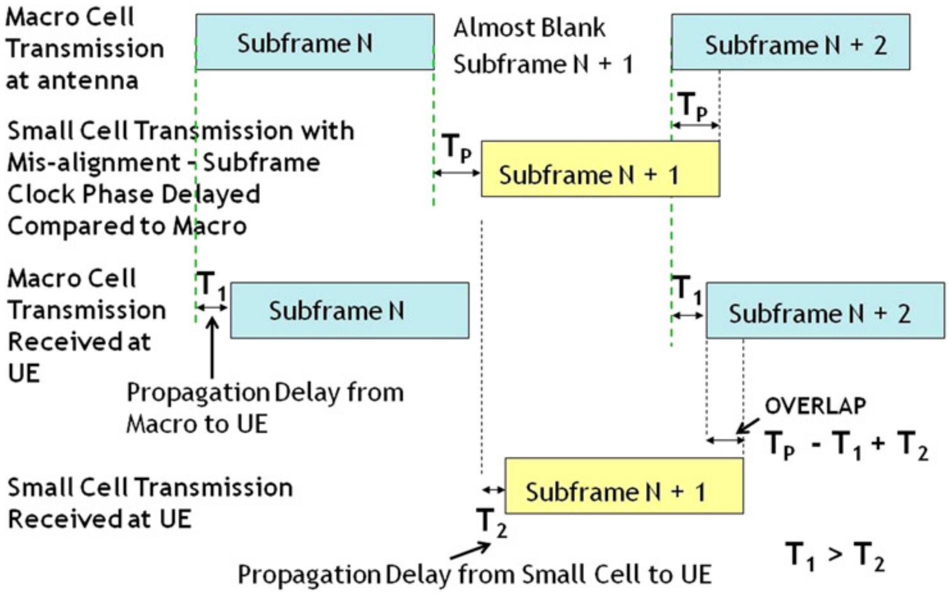

Fig. 3 *Impact of phase mis-alignment for scenario 2*

Fig. 3 shows the timing diagram of scenario 2 where the small cell's sub-frame timing phase is delayed relative to that of the macro. Here, the trailing edge of the small cell's $N+1$th sub-frame overlaps with the leading edge of the macro's $N+2$nd sub-frame. The overlap time in this scenario is given by

$$T_{\text{overlap}} = T_P - T_1 + T_2 = T_P - (T_1 - T_2) \quad (2)$$

Comparing (1) and (2), we find that the overlap period is larger for scenario 1. In scenario 1, the differential propagation delay increases the overlap period, whereas in scenario 2 it reduces the overlap period. As a result, scenario 1 is the worst-case scenario for eICIC operation since the overlap period is larger and hence more detrimental.

3 Deriving the phase synchronisation requirement

We now analyse scenario 1 as it requires the most stringent phase sync requirement.

In scenario 1, the leading edge of the small cell's sub-frame overlaps with the trailing edge of the macro's previous sub-frame. The very first signal in a sub-frame is the cyclic prefix of the first orthogonal frequency division multiplexed (OFDM) symbol. As long as the overlap is confined to be within the duration of the cyclic prefix of the first OFDM symbol of the small cell sub-frame, there is no performance impact as the cyclic prefixes are discarded by the UE receiver. A larger overlap can cause a performance impact. Hence, we need

$$T_{\text{overlap}} < \text{First Cyclic Prefix Period} \quad (3)$$

The time duration of the cyclic prefix of the first OFDM symbol is 5.216 µs as defined by the LTE standard. Substituting (1) into (3)

$$T_P + T_{\text{Diff\_Prop\_Delay\_Time}} < 5.216\ \mu\text{s} \quad (4)$$

From (1) and (4), a number of conclusions can be reached:

(i) Both T_P and $T_{\text{Diff\_Prop\_Delay\_Time}}$ are time-varying quantities. T_P varies in a statistical fashion based on the PLL's characteristics. $T_{\text{Diff\_Prop\_Delay\_Time}}$ will vary dependent on UE position and speed and will also vary from UE from UE.

(ii) It is not possible to achieve zero overlap even with perfect synchronisation of the macro and small cell timing because of the contribution from the differential propagation path delay.

(iii) A single value for the phase synchronisation is not sufficient for all possible deployment scenarios.

It is difficult to derive a phase synchronisation requirement from (4) because of the dynamic time-varying nature of the components. We can however derive a simpler version of (4) by setting $T_{\text{Diff\_Prop\_Delay\_Time}}$ to the maximum differential propagation delay possible. The maximum possible $T_{\text{Diff\_Prop\_Delay\_Time}}$ for scenario 1 occurs when an UE is present at the very edge of the macro cell radius as this maximises the macro propagation time T_1. Assuming line of sight propagation which is reasonable for outdoor deployment, we can express the maximum differential propagation delay in terms of the cell radius of the macro and small cell as follows

$$T_{\text{Max\_Diff\_Prop\_Delay\_Time}} = \frac{1}{C}(\text{Radius}_\text{M} - \text{Radius}_\text{SC}) \quad (5)$$

where C is the speed of light in metres per second, Radius_SC is the cell radius of the small cell in metres, Radius_M is the cell radius of the macro cell in metres and $\text{Radius}_\text{SC} < \text{Radius}_\text{M}$.

Substituting (5) into (4), we get the relationship for the phase synchronisation requirement as follows

$$T_P + \frac{1}{3 \times 10^8}(\text{Radius}_\text{M} - \text{Radius}_\text{SC}) < 5.216 \times 10^{-6} \quad (6)$$

From (6), since the radius of the macro cell and small cell are known, it is quite straightforward to determine the maximum allowed value of the phase difference T_P in seconds that ensures zero overlap of the sub-frames. As an example, for $\text{Radius}_\text{M} = 1$ km and $\text{Radius}_\text{SC} = 100$ m, the T_P requirement is calculated to be <2.216 µs.

4 Conclusion

This paper has determined the worst-case scenario required to derive the phase synchronisation requirement for zero overlap for eICIC. It has also developed a relationship showing how the various factors that impact the overlap are related to one another and how a requirement for the phase synchronisation can be specified. This will enable operators to properly engineer a HetNet deployment without performance degradation due to the phase mis-alignment.

5 References

[1] Vasudevan S., Pupala R.N., Sivanesan K.: 'Dynamic eICIC – a proactive strategy for improving spectral efficiencies of heterogeneous LTE cellular networks by leveraging user mobility and traffic dynamics', *IEEE Trans. Wirel. Commun.*, 2013, **12**, (10), pp. 4956–4969, doi: 10.1109/TWC.2013.081413.121651

[2] 3GPP TS 36.104: 'Base station (BS) radio transmission and reception'

[3] Bladsjo D., Hogan M., Ruffini S.: 'Synchronization aspects in small cells', *IEEE Commun. Mag.*, 2013, **51**, (9), pp. 70–77, doi: 10.1109/MCOM.2013.6588653