Synchronization in Industrial IoT: Impact of propagation delay on time error

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***Abstract*—The growing needs for wireless connectivity in smart industries raises opportunities for mobile service providers as well as industrial players, also known as verticals. This inevitably has increased challenges for both the parties involved. This is increasingly true for timing and synchronization requirements. Within this context, in this article, we present a detailed analysis of 'time synchronization errors'. These errors are commonly known to affect the delivery of accurate time needed to synchronize the robots and machines present inside the Industrial Internet of Things (IIoT) domain. To eliminate such errors, we propose a novel compensation technique to compensate for the random errors which occur due to the propagation delay in the wireless medium. The article concludes by providing numerous results based on simulations with discussions proving the efficacy of our proposal.**

***Index Terms*—Time synchronization, propagating delay compensation, time error, 5G/B5G, Industry 4.0/5.0.**

I. Introduction

Time synchronization is increasingly vital for wired and wireless communication, especially in time-critical industrial applications. This necessity is driven by the demands of Industry 4.0 and the forthcoming Industry 5.0, emphasizing the need for precise time synchronization.

In particular the end-to-end (starting from the time source - GNSS-based or IEEE 1588-based, until the end robot) time synchronization requirements are defined to be no more than 1 microsecond for end-to-end time sensitive communications, in the context of 3GPP Release 16 specifications defined for 5G [1]. This involves transporting timing packets over wired networks as well as wireless networks. Transporting timing packets over wired networks is relatively simple, due to the fact that the errors which accumulate over a wired medium (fibre, copper cables, etc.) could be estimated in advance and could be eliminated using compensation techniques. One of the most known compensation techniques for wired medium is 'Calibration' [4]. On the other hand, transporting timing over wireless medium is more difficult, due to the nature of the wireless medium itself. The air interface, also known as the radio interface is known to encounter several types of errors which are mostly random. Some of known factors to influence the errors over the air interface are directly related to channel conditions, such as multi-path, fading, mobility, etc. Our focus in this paper is on error compensation for the wireless medium, with particular attention paid to the study and analysis of various errors which occur in the wireless medium while trying to establish a synchronisation over-the-air between the User Equipment (UE) and the Base Station (BS). Our contributions in this paper are as follows:

- Time Compensation Technique: We propose a time compensation technique specifically designed to address the time error caused by the wireless medium. We also provide a comprehensive analysis and understanding of the impact of time error on the synchronization accuracy, using detailed simulations. This proposed technique effectively minimizes the synchronization errors.
- Signal Synchronization based only on Downlink: In our research, we propose an approach to synchronize the clocks of User Equipment (UEs) with static locations, using only a downlink signal for the case of smart factories. This method significantly reduces the overall time error thereby increasing synchronising accuracy, ensuring highly accurate and precise synchronization. By eliminating the need for additional signals, such as uplink signals, or complex synchronization mechanisms, our approach simplifies the synchronization process while maintaining good accuracy levels. In the context of our paper, the UE could be a 'relay' placed between the Base Station (BS) and the robots of the factory or the UE may represent the robots themselves directly. We assume that this device will be confined to a given factory location.

Our paper is organised as follows. Section II provides a detailed analysis on the various factors that affect the Propagation Delay (PD). Section III proposes our novel technique to compensate for the random errors which occur due to the propagation delay in the wireless medium. Our error compensation technique leverages on the existing methods of error calculation standardised by 3GPP and therefore does not require any changes to existing implementations of the mobile BSs or the UEs. Our results in Section IV show that our compensation technique satisfies the emerging demands of 5G, as defined in [1]. Section V concludes this work.

II. Background and Related Works

Similar to 4G, 5G uses Synchronization Signal Block (SSB) to synchronize the UEs 'over-the-air'. However, the frame structure of 5G SSB is quite different than that of 4G. The frame structure used for over-the-air synchronization is defined in the 3GPP specifications [5]. The SSB consists of 4 OFDM symbols, the first for Primary Synchronization Signal (PSS), the second for Secondary Synchronization Signal (SSS), and the rest for Physical Broadcast Channel (PBCH). Synchronization is established through an exchange of these signals between the BS and the UE, in frequency domain as well as in time domain. This enables synchronisation in both frequency as well as in time. More details on this initial attach process could be found in [6].

Propagation delay (PD), represented from here onwards mathematically as P_{DL}, is defined as the amount of time that a signal needs to be received by the UE from the BS; the greater the distance between the UE and the BS, the higher the P_{DL} would be [7]. This will cause the local clock present inside the UE, T^{UE}, to lag behind the reference BS local clock, T^{BS}. The most commonly known methods to estimate propagation delay are based on Timing Advance (TA) and Round Trip Time (RTT) methods. These are legacy techniques and for in-depth details, please refer [8]. These two methods date back to 3G. Although both these methods are able to fulfil the existing 3GPP requirements for time synchronization, we argue that they may not satisfy the emerging synchronization requirements of the future Industrial Internet of Things (IIoT) domain. For instance, 3GPP TS 23.501 [1] cites that the most demanding synchronisation requirement in the context of smart industries is 900 ns, which has been defined for motion-to-motion control application within a smart grid.

In order to improve the time synchronization accuracy for 5G, new approaches have been introduced. It is worth mentioning here that propagation delay estimation and compensation, while remaining a very important operational subject, remains an obscure field of research. While the number of related works directly implicating this subject is very limited, there are a handful of very interesting related works. To point a few, the authors of [9] proposed to use Channel State Information Reference Signal (CSI-RS) instead of SSB to benefit from its higher bandwidth to cover larger distance between the base station and User Equipment (UE). The results show that the proposed signals cover more distance between UE and gNB compared to the usual synchronization signals. However, their results were limited only for sub-carrier spacing of 15 kHz for 3.6 MHz carrier frequency bandwidth for the SSB signals. In [7] the authors chose another different method for time synchronization. They used multiple TA measurements to estimate the position of UE in order to determine the PD. Their technique causes significant overhead over the wireless medium and is not suitable to satisfy the synchronisation requirements of 5G, notably the 900 ns [1]. In [2], the authors introduced a propagation delay estimation and compensation technique which combines both TA and RTT methods. They talked about the downlink/uplink time synchronization budget from a RAN perspective. This solution, as they have pointed-out themselves, has the disadvantages of complexity and wasted resources. Following this in [3], the authors investigate frequency and scalability aspects of over-the-air time synchronization. Their performance evaluation reveals the conditions under which 1 microsecond or less requirement for time synchronization can be achieved. They adopt an approach where the accuracy of time synchronization is achieved through the use of 'special equipment' in the presence of clock drift and different air-interface timing errors related to reference time indication. The complexity lies within the fact that the network requires an upgrade for the use of such 'special equipment'.

Unlike the above mentioned works, through our work, we show that our proposal is efficient in order to satisfy the emerging demands of 5G while satisfying the many different criteria such as different Sub Carrier Spacing (SCS), different carrier frequency bandwidth, different channel models, etc., without creating any additional impact to the existing implementations or network operations. This means network operators could leverage on their already deployed 5G base stations (gNBs) in order to fulfil even future emerging synchronisation demands from verticals. Furthermore, our technique uses only downlink synchronization signals between UE and 5G base station without the need for uplink transmissions. This may simplify compensation calculation, reduce system latency, and improve the performance of the network since there will be fewer transmissions (no uplink transmissions), less consumed power, and fewer resource allocations.

III. On the Impact of Propagation Delay Estimation And Compensation

The main challenge in estimating the total synchronization error is finding the propagation delay error and compensating for it. While doing this, there are different types of errors that come into picture. They are:

Base station timing error: on the base station side, 3GPP defines the maximum Time Alignment Error (TAE) as a requirement [15], and it is caused due to the mismatch between the frames transmitted from different radio units (or antenna connectors). This mismatch can be caused by the clock drift or due to the delays incurred by the synchronization protocols. Table I summarizes the timing values of TAE specified by 3GPP for different scenarios . Two types of base station errors are involved in this exchange: the base station Transmission timing error listed in Table I and the base station detection error, which is a constant value of 100 ns, shown in [15].

TABLE I: TAE for BS specified by 3GPP

Scenarios	Max TAE
MIMO transmission	65 ns
Intra-band contiguous carrier aggregation	260ns
Intra-band non-contiguous carrier aggregation,	3µs
Inter-band carrier aggregation,	3µs

User Equipment (UE) error: Uplink and downlink exchanges between the UE and BS lead to two main errors related to the UE: the initial transmit timing error, denoted in this paper as $E_{UE,UL,Tx}$ and referred by 3GPP as T_e, is listed in Table II. The second error is the downlink reception error observed in the UE, denoted as $E_{UE,DL,Rx}$. The downlink frame time on UE side represents the time of arrival (ToA) of the downlink signal. The downlink frame timing detection error $E_{UE,DL,Rx}$ depends on SCS of the uplink signals.

TABLE II: T_e Timing Error Limit

Frequency Range	SCS of SSB signals (KHZ)	SCS of uplink signals (kHz)	T_e
1	15	15	12*64*Tc
		30	10*64*Tc
		60	10*64*Tc
	30	15	8*64*Tc
		30	8*64*Tc
		60	7*64*Tc
2	120	60	3.5*64*Tc
		120	3.5*64*Tc
	240	60	3*64*Tc
		120	3*64*Tc

Note : Tc is the basic timing unit defined in TS 38.211 [11]

Figure 1 shows various errors due to base station and UE.

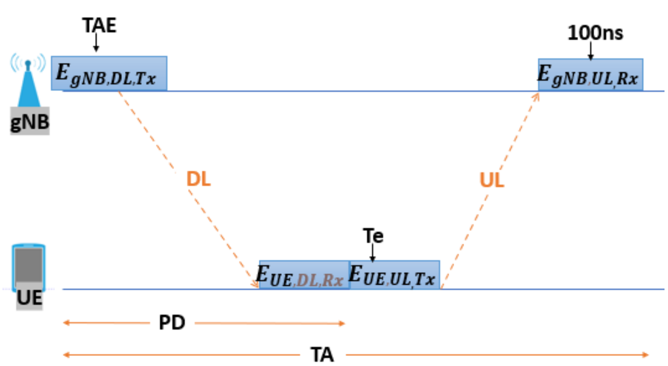

Fig. 1: Time errors inside BS (5G gNB here) and UE

Propagation delay error: The channel also causes a significant error called the propagation delay error. It cannot be fixed and it remains uncertain due to multi-path propagation, UE's mobility, atmospheric conditions, asymmetry between downlink and uplink, etc. The various (non-exhaustive) factors which contribute to propagation delay error are:

a) Pathloss: Radio propagation produces a reduction in power density of an electromagnetic wave as it propagates through space, causing reception errors. 3GPP has defined different path-loss models which allow to simulate different scenarios (please refer to Table 7.4.1-1 of [12]).

b) Channel: The wireless channel's characteristics can have an impact on the timing synchronization procedure due to multi-path propagation and interference. 3GPP defines two channel models for link level simulations, namely TDL and CDL [12]. TDL is the model of taps with different delays (therefore the name Tapped Delay Line); each tap is modeled as a random variable. Clustered Delay Line (CDL) models a received signal consisting of multiple delayed clusters. Multipath fading is simulated by adding attenuated and phase shifted copies to the transmitted signal.

c) Shadowing: The existence of obstacles between the transmitter and the receiver causes the shadowing effect. For this study, we additionally assess the situation for line-of-sight (LOS) and non-line-of-sight (NLOS).

A. Proposal to estimate PD for devices

We propose our method for estimating the propagation delay for a known UE with a fixed TX-RX distance, in order to compensate for the estimated PD. We then investigate the effect of the channel conditions (such as path-loss, multipath, and shadowing) between UE and BS. We assume a use case with stationary devices, considering control-to-control communication for industrial controllers with a service area of 100 m^2, which requires a total time error budget of 900 ns [1]. In this use case, majority of IoT devices are immobile or have limited mobility (mobility confined to a space and does not exceed $5km/h$) in small service areas [13]. Therefore we base our hypothesis on the assumption that the distances between the base station and the UE do not vary randomly. This allows us to establish fixed values for propagation delay estimation and compensate for it relatively 'easily' rather than using TA or RTT methods. By assuming a fixed distance between the TX and the RX, the remaining error gets limited to channel conditions such as multipath or fading. Only variations due to parameters like atmospheric conditions could have a severe impact on the PD.

In our case, only a downlink signal from the base station to the UE is used, without the need to use an uplink signal as in the case of TA or RTT methods. This enables very little overhead over the dedicated wireless medium. In addition this decreases the total time error in the synchronization procedure, because the errors $E_{UE,UL,Tx}$ or $E_{BS,UL,Rx}$ become absent. Our proposal considers a stationary UE or a UE with mobility in limited area, such that the approximate location is known. It is realistic to assume that we know the location of the smart factory. In the case of higher mobility, we can use a fixed relay UE, placed inside the smart factory, to redistribute the time synchronization received from the base station.

Thus, calculation of propagation delay compensation error assumes knowledge of the approximate distance between the base station and the UE, as from above we consider the UE confined to a factory location. With a Non-Disclosure Agreement (NDA), it is possible to obtain the approximate positions of the Factory or UEs present either inside or around the premises of the factory for a first use. This will introduce some error, but this error stays minimal as specified in the next paragraph. In addition, we would need only a one-way downlink signal instead of the two-way signals (downlink and uplink as in TA or RTT). This enables lower overhead over the dedicated wireless medium, in addition to decreasing the time to synchronize the UEs with less time error. With this, we deduce the timing of UE, T^{UE} as:

$$T^{UE} = T^{BS} + P_{DL} + E_{Total} \tag{1}$$

The total remaining error, E_{Total}, is traditionally estimated by adding the different downlink and uplink errors as

$E_{UE,UL,Tx}$, $E_{BS,UL,Rx}$, $E_{UE,DL,Rx}$, $E_{UE,UL,Tx}$, the channel transmission errors and errors related to the calculation of the time advance or RTT. However in our proposal, the total remaining error is derived from only using the downlink errors $E_{UE,DL,Rx}$ and $E_{gNB,DL,Tx}$, in addition to the error of the estimated distance, $E_{d,est}$, and the error of the transmission channel, Err_{chan}, which is shown in eq. (2) and Figure 2.

$$E_{Total} = E_{d,est} + Err_{chan} + E_{gNB,DL,Tx} + E_{UE,DL,Rx} \tag{2}$$

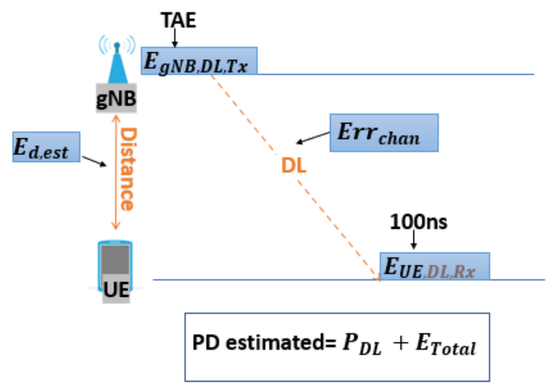

Fig. 2: Illustration of proposed propagation delay estimation

Our proposal involves the reference time to be sent by the mobile network clock (base station). For low mobility devices in the IIoT domain, the clock on the device (equation 1) is adjusted by using the propagation delay compensation P_{DL}, estimated using the distance between UE or the smart factory, which is fixed in our use case, and gNB. The proposed total propagation delay will be the sum of propagation delay compensation P_{DL} and the calculated error E_{Total} as explained in Figure 2. $E_{d,est}$ is low in our case, since a localisation error of 10 m will lead to 33.33 ns of error considering the speed of light, and we assume that the location of smart factory is known with such error margin. It should be mentioned that for a distance below 200 m, there is no need for propagation delay estimation and compensation [15]. The timing errors due to transmitters and receivers of gNB and UE would be constant, since they remain to be the same physical components. Table I presents $E_{gNB,DL,Tx}$, and Table II presents $E_{UE,DL,Rx}$. The other part of error Err_{chan} will be due to multipath and synchronisation error losses. We study this error through simulations in the following section.

IV. Numerical results and analysis

In this section, we outline the simulations that were used to estimate the only unknown variable in our equation 2, in order to better calculate the total error E_{Total}.

A. Simulation setup and parameters

Numerous simulations were conducted using the 5G toolbox of MATLAB. We simulated a signal of 6 GHz. By carefully simulating several scenarios, we analyse the occurrence of remaining error and investigate whether we respect the 3GPP specification, i.e. the budget of 900 ns for control-to-control communication for industrial controllers with a service area of 100 m² [1].

B. Step-by-step process of our simulations

We simulated a TDL-C channel. This created multiple delayed versions of the input signal. By doing this, we were able to simulate a realistic multipath channel. We then added a path loss that is compliant to the 3GPP specification [12]. We generated the synchronization signal block (SSB) mentioned in [11]. We then used FFT in order to transform the generated SSB from frequency domain to time domain. The transformed signal is ‘delayed’ before transmitted. This ‘external delay’ is added in order to inter-correlate the received signal and the local reference signal. This inter-correlation allows us to compensate the propagation delay value using the distance and the speed of light. The peak of the correlation represents the estimated propagation delay with channel effects.

C. Analysis of the proposed method for delay compensation

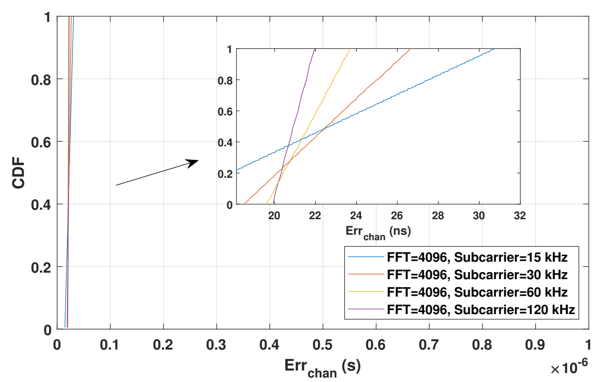

Fig. 3: CDF plot for Err_{chan} for variable distances ranging from 0 to 1km and delay spread of 30 ns

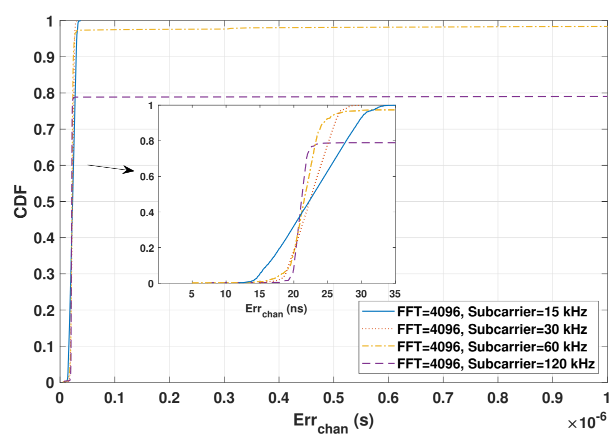

Fig. 4: CDF plot for Err_{chan} for variable distances ranging from 0 to 3km and delay spread of 30 ns

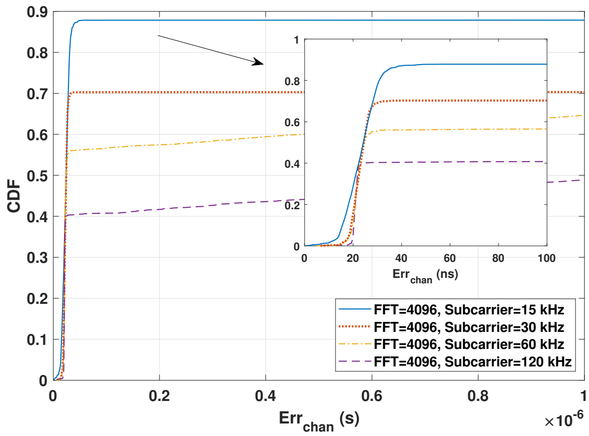

Fig. 5: CDF plot for Err_{chan} for variable distances ranging from 0 to 6km and delay spread of 30 ns

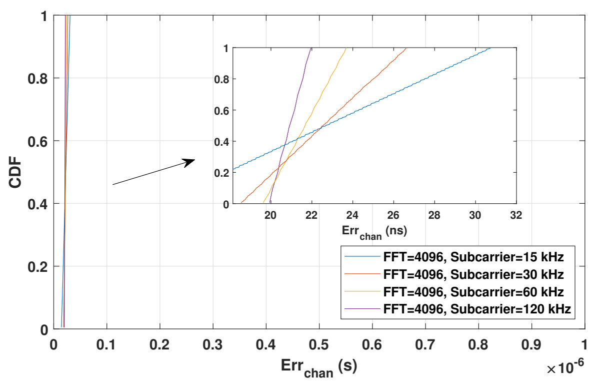

Fig. 6: CDF plot for Err_{chan} for variable distances ranging from 0 to 1km and delay spread of 300 ns

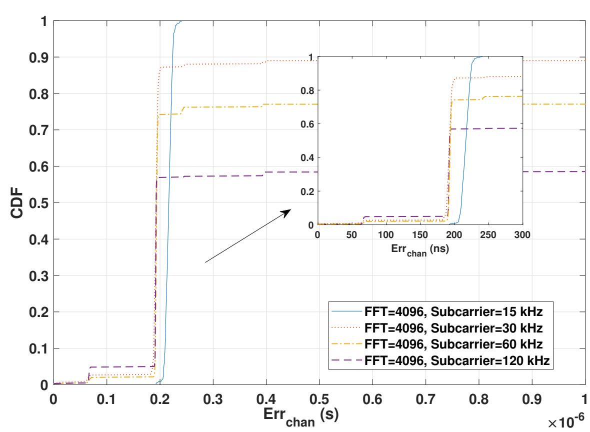

Fig. 7: CDF plot for Err_{chan} for variable distances ranging from 0 to 3 km and delay spread of 300 ns

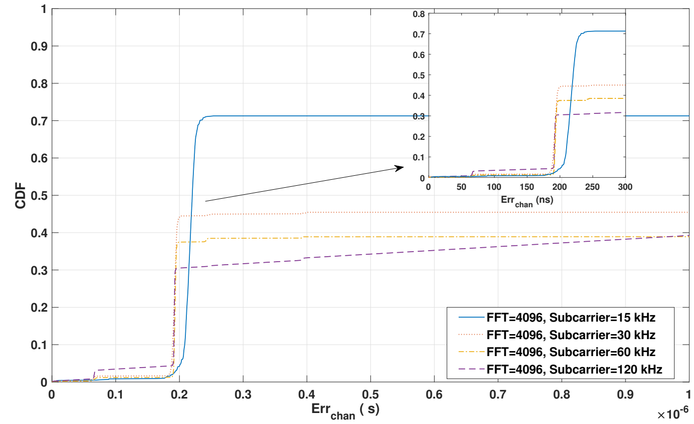

Fig. 8: CDF plot for Err_{chan} for variable distances ranging from 0 to 6 km and delay spread of 300 ns

We analyse our link-level simulations here. We analyse Err_{chan} and results show that a lot of error budget (for a target $E_{total} < 900$ ns) is still remaining to account for $E_{d,est}$ (33.33 ns for up to 10m of localisation error), $E_{gNB,DL,Tx}$ (around 65 ns) and $E_{UE,DL,Rx}$ (around 100 ns). Next, we add a detailed analysis for our simulation results, and discuss different parameters which affect synchronization error.

*a) **Distance vs Time error**:* The results show the impact of the maximum distance. Several simulations are run with UE randomly placed up to a given maximum distance. We will examine cumulative distribution function (CDF) which shows the probability (Y-axis) of achieving a value lower than or equal to a given point on the X-axis. Figures 3, 4, 5, show CDF of Err_{chan} over a maximum range of distances up to 1 km, 3 km, and 6 km respectively. These ranges are reasonable as we are considered rural environment for IIoT factories. On the X axis, we plot the time error values Err_{chanl} up to 1 μs. We also include zoomed figures to show the details. First we fixed the delay spread to 30ns. For SCS 15 kHz, we observe that for 88% of times Err_{chan} error is low for a maximum distance of 6 km. At other times the synchronisation is lost due to reception errors. For maximum distance of 3km or less, we have low error for almost 100% of times. Similar simulations were conducted for delay spread of 300 ns (as delay spread can be high with such high distances). Results are shown in Figures 6, 7, 8. For SCS 15 kHz, the error now is limited to 200 ns approx. for 70% of times with max. distance of 6 km and almost 100% of times with max distance of 3 km or less. We can also observe that synchronisation loss occurs more often when the delay spread is increased. This is explained by the increase in Inter Symbol Interference (ISI). For example for same maximum distance of 6 km, CDF shows that, when compared side by side for different DSs, synchronisation loss occurs more often when delay spread is higher i.e. 300 ns as compared to 30 ns.

*b) **Sub Carrier Spacing vs Time error**:* In general, we can see that sub-carrier spacing of 15 kHz is relatively more robust as compared to other SCS values. For maximum delay spread of 300 ns, it can satisfy the requirements of error < 900 ns in 70% of cases when maximum distance is 6 km and close to 100% when maximum distance is 3 km or less. Other SCS values perform relatively poorer with worse values for highest SCS. For example for SCS 120 kHz, the synchronisation requirement is satisfied only for 30% and 55% with maximum distance of 6 km and 3 km respectively. This is due to decreasing cyclic prefix interval leading to increased Inter Symbol Interference (ISI). Nevertheless, all SCS satisfy the synchronisation requirements almost 100% of times when the maximum distance is 1 km.

*c) **Delay spread vs Time error**:* We may also observe how different SCS are affected by a random value delay spread (DS) in Figure 9. DS refers to the difference of the time of arrival of multiple visions of the same signal at the receiver due to the multipaths. We vary DS for analysis because DS can vary from environment to environment. A higher DS indicates a less robust channel with a significant time difference between the earliest and latest signal arrivals, which leads to more ISI.

Figure 9 shows how DS affects time synchronization error and illustrates the CDF of Err_{chan} over a range of DS values between 32 ns and 1148 ns, as they are the minimum and maximum values of DS suggested by 3GPP [12] for different scenarios of Urban Macro (UMa), Rural Macro (RMa) and RMa Outdoor-to-Indoor (RMa O2I). With SCS of 15 kHz, 77% of transmitted signals had a Err_{chan} of less than 700 ns (while rest of the time the synchronisation was lost), compared to only 10% with SCS of 120 kHz. Higher sub-carrier spacing can result in a broader channel response, which lengthens the channel's delay spread. Thus, SCS should be chosen carefully depending on application needs and the traits of the wireless channel, including the delay spread.

*d) **Frequency vs Time error**:* We used a 6 GHz carrier frequency for the conducted simulation. Adopting high carrier frequencies opens the possibility of using new sub-carrier spacing of 60 kHz and 120 kHz, which may increase sensitivity to frequency and phase noise, but decrease resistance to Doppler shift. The transmitted symbols have a shorter duration, using higher sub-carrier spacing also reduces the effect of ISI.

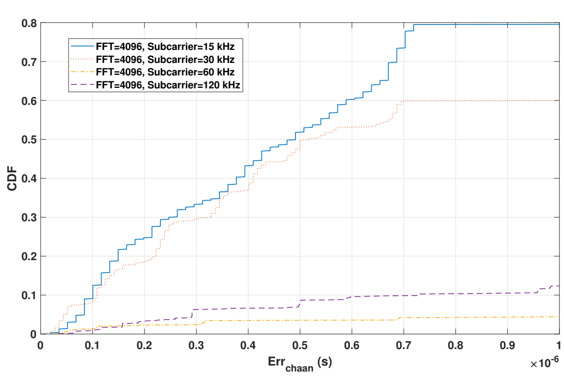

Fig. 9: CDF plot for Err_{chan} for a fixed distance of 3 km and variable random delay spread.

V. Discussions and Conclusion

This paper proposed a new method for estimating and compensating propagation delay (PD). The idea is to correct the time error caused by the wireless medium when time synchronisation is delivered directly from the MNO's BSs. Only one-way downlink signal is used (instead of the classical two-way uplink-downlink) in order to reduce the signalling overhead. This allowed to improve the synchronisation accuracy for IIoT devices inside factories. Different scenarios, notably Distance vs Time Error, Sub-carrier Spacing vs Time Error, Delay Spread vs Time Error were evaluated. The best possible criteria which resulted in the least time error value were analyzed in order to obtain the best time synchronisation values. Our results reveal the impact of the transmission channel. Overall conclusions show that the distance between the BS and the UE has the maximum impact on the time error regardless of the application, while sub carrier spacing and delay spread should be chosen carefully depending on the application needs and the traits of the wireless channel. Future works would include advanced and precise models such as ray tracing models considering Refractive Index Surface (RIS) that would allow for more fine tuning of the time errors leading to better time synchronization values. Practical prototype in actual industrial IoT environments may be foreseen to confirm the effectiveness of the proposed solution.

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