

Time Synchronization in 5G Wireless Edge: Requirements and Solutions for Critical MTC

Aamir Mahmood, Muhammad Ikram Ashraf, Mikael Gidlund, Johan Torsner, and Joachim Sachs

ABSTRACT

The wireless edge is about distributing intelligence to wireless devices wherein the distribution of accurate time reference is essential for time-critical machine-type communication (cMTC). In 5G-based cMTC, enabling time synchronization in the wireless edge means moving beyond the current synchronization needs and solutions in 5G radio access. In this article, we analyze the device-level synchronization needs of potential cMTC applications: industrial automation, power distribution, vehicular communication, and live audio/video production. We present an over-the-air synchronization scheme comprising 5G air interface parameters and discuss their associated timing errors. We evaluate the estimation error in device-to-base-station propagation delay from timing advance under random errors and show how to reduce the estimation error. In the end, we identify the random errors specific to dense multipath fading environments and discuss countermeasures.

INTRODUCTION

The very vision of Industry 4.0 — making industrial processes intelligent, efficient, and safer — is tied to real-time automation and control of dynamic industrial systems over wireless networks. However, what is achievable by existing wireless networking solutions in terms of communication reliability and latency is not sufficient for critical machine-type communication (cMTC). Instead, ultra-reliable and low-latency communication (URLLC) is required. However, the key sectors in cMTC — factory automation, power distribution, vehicular communication, live audio/video production, and so on [1] — require precise time synchronization up to the device level. If we take discrete manufacturing as an example, devices require synchronized coordination for timely/sequential execution of tasks such as assembly, picking, welding, and palletizing. In power distribution, monitoring and fault localization require perfectly synchronized measurement units. Hence, in cMTC applications, where ultra-reliability is vital for the safety of processes, equipment, and users and low latency for real-time functionality of applications, time synchronization is intrinsic to real-time coordination and interaction among devices.

Supporting determinism, in terms of reliability of 10^{-5} – 10^{-6} and latency up to 1 ms,

and synchronism with jitter below 1 μ s is the focus of Third Generation Partnership Project (3GPP) use cases within fifth generation (5G) URLLC. These requirements add challenges to the design of the radio access network (RAN) from the physical layer leading up to the radio resource control (RRC) layer. 3GPP Releases 15 and 16 specify new features for New Radio (NR) including faster scheduling, short and robust transmissions, repetitions, faster retransmissions, preemption, and packet duplication as well as multiconnectivity architectures [2]. However, the importance of time synchronization, which is a crucial component of the new RAN technologies and services, moves beyond RAN to provide an accurate time instant on a common time base to the devices and is perceived as a key enabler for cMTC applications. The devices can achieve perfect time alignment to the coordinated universal time (UTC) by employing a global positioning system (GPS) receiver; however, such a solution is expensive and mainly impractical for indoor industrial deployments.

In industrial measurement and control systems, time is synchronized separately from the data flow [3]. Since many applications require synchronization, it is an essential part of the Ethernet-based networks such as PROFINET and the rapidly evolving open standard on time-sensitive networking (TSN) by the IEEE 802.1 task group. TSN defines a series of standards to support URLLC use cases over best-effort Ethernet networks. The synchronization procedures for industrial systems are rooted in Precision Time Protocol (PTP), defined by the IEEE 1588 standard. All Ethernet-based automation networks utilize IEEE 1588 variants, known as PTP profiles. In TSN, for instance, the transport of precise timing and synchronization is performed using the IEEE 802.1AS standard.

Establishing over-the-air (OTA) accurate time reference at the device level requires transfer/exchange of timestamps between controller (i.e., base station, BS) and devices. Additionally, 5G is expected to coexist with existing industrial Ethernet and emerging TSN-based industrial Ethernet even in greenfield deployments. Therefore, the integration of 5G into existing industrial connectivity fabric would require devices to maintain synchronization with local time domains within a mixed 5G-Ethernet network as depicted in Fig. 1. The transfer of precise timing

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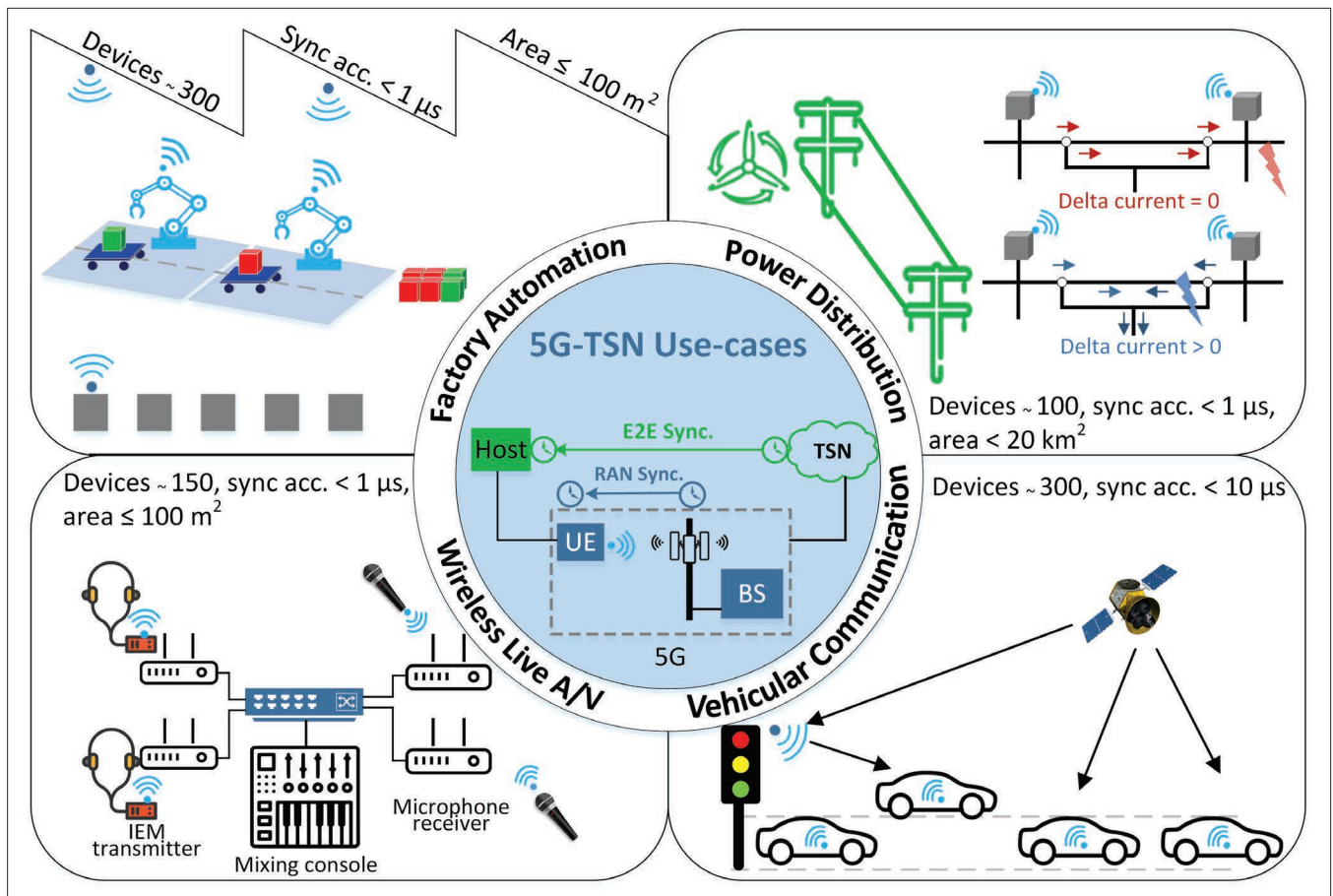


Figure 1. Critical machine type communication (cMTC) use cases requiring device-level time synchronization and an enabling solution over 5G-TSN network.

reference (absolute or local domain time) via the 5G system to the devices using OTA synchronization is currently being investigated in 3GPP Release 16 [4].

Nevertheless, securing robust distribution of reference time into the network has many associated challenges. Following the existing procedures in cellular systems, the devices must compensate for the propagation delay in the reference time. Typically, this is achieved using timing advance (TA) – the frame alignment procedure as used in LTE and the 5G NR radio interface. However, TA is an approximation of device-to-BS (D2B) propagation time since each TA value corresponds to a certain range of time of arrival (TOA) values. Both the limited granularity of TA and the random perturbations in TOA due to the measurement and multipath errors, respectively, can introduce inaccuracy in reference time. Therefore, the impact of TA-related errors need careful investigation and correction to meet the device-level synchronization target.

In the rest of this article, we present the role of time synchronization in multiple cMTC use cases. We discuss the transition of 5G into industrial networks. We present the 5G NR procedures and the associated timing errors to enable device-level synchronization. We quantify the errors in propagation delay due to TA and propose an improvement. An outline of new research directions to enhance synchronization accuracy in 5G concludes the article.

USE CASES OF DEVICE-LEVEL TIME SYNCHRONIZATION

Any application requiring imperceptible lag in executing orders or reporting remote events is a potential use case of device-level time synchronization. Albeit 5G-cMTC outlines several URLLC cases and their synchronization requirements in [1, 4], we now elaborate the ones with device-level synchronization requirements (Fig. 1).

FACTORY AUTOMATION

Isochronous Real-Time Communication: Critical industrial automation applications exhibit stringent requirements on communication latency and reliability, as well as on time-synchronized coordination among machines and robots. In particular, in closed-loop motion control – in packaging, printing, and symmetrical welding/polishing – machines execute meticulously sequenced real-time tasks isochronously. Typically, a sequence of real-time control command/response frames is communicated over the communication links between controller and devices. To ensure smooth and deterministic execution of the production cycle, timely coordination among devices/machines must be accomplished, which is possible only if the devices are synchronized to a common time reference with clock disparity of less than 1 μs [4].

Data Fusion: Robust and accurate synchronization is required for meaningful sensor fusion, post-processing, and network analytics. In low-la-

tency time-sensitive applications, the responses from various sensors must be fused to drive the logic behind the control systems. Such data fusion requires a synchronized collection of the events. Besides, the Industrial Internet of Things (IIoT) is meant to increase operational efficiency based on data analytics of sensory information; however, the time context of sensor events must be factored in to make analytics definitive.

POWER DISTRIBUTION NETWORKS

Managing power distribution networks — with an increasing amount of distributed energy resources and an increasing need for reliability, efficiency, and flexibility — requires enhanced communication technologies/services for functions such as protection, control, and remote monitoring [5].

Fault Protection: In a transmission/distribution line, usually a line differential protection system detects faults based on a periodic sampling of electric current between the two relay devices [5]. When the relays differ in measurements, the system triggers the fault protection procedure (i.e., it sends a trip command to the relevant breaker). For such a fault detection procedure to work correctly, relays are synchronized with an accuracy of less than 20 μ s.

Control and Optimization: With the increasing penetration of renewable resources, control and optimization are required at both the transmission and distribution levels. A vital control task is to match power supply and demand as per the voltage and frequency regulations, where a control strategy, either centralized or distributed, is devised based on fine-grained information of measured electrical values of the load and the source. Although reliability and latency of reporting such information are specific to a control strategy, time synchronization accuracy is less demanding.

Monitoring and Diagnostics: Situational awareness and insights on the condition of distribution systems depend on measurements and analytics. There is a growing interest in instrumenting power distribution systems with phase measurement unit (PMU)-like technology. PMUs take time-synchronized measurements of voltage and current to activate a monitoring system for fault diagnosis. For instance, by synchronously measuring electric wave generated by a fault location at two points along the distribution line, the monitoring system can estimate the fault location based on the reported timing information. Precision in physical measurements, time synchronization accuracy, and the ability to cross-reference event locations offer more in-depth insights into the distribution network. Usually, synchronization accuracy of higher than 1ms is required to keep fault location uncertainty below 300 m [6].

VEHICULAR COMMUNICATION

Vehicular communication is about wireless transactions among nearby vehicles and infrastructure, vehicle-to-everything (V2X) communication, which can enable cooperative intelligent transport systems capable of reducing traffic congestion and improving road safety. Ensuring timely and robust delivery of safety-related messages is critical. Examples of safety-related operations are forward collision warning and emergency electronic brake lights, which alert drivers about possible

collisions ahead. To execute these operations, vehicles need to exchange position, event time-stamp, brake status, and heading information from onboard GPS. Furthermore, to function such coordination as per the age of information, the applications require that all the involved vehicles are synchronized to the same reference clock, usually provided by GPS. However, for such critical operations, a backup time synchronization service must be provided by the roadside communication infrastructure to handle GPS signal blockages and outages [7].

WIRELESS LIVE AUDIO/VIDEO PRODUCTION

Wireless audio/video (A/V) equipment used for real-time production of audio-visual information, be it in the entertainment industry or live events and conferences, are denoted by the term program making and special events (PMSE). Usually, the wireless A/V production equipment includes cameras, microphones, in-ear monitors (IEM), conference systems, and mixing consoles. PMSE use cases are diverse, each commonly being used for a limited duration in a confined local geographical area. In terms of communication requirements of typical live A/V production setups, low-latency and ultra-reliable transmissions are pivotal to avoid failures and perceptible corruption of the media content. Moreover, perfect synchronization is crucial to minimize jitter among captured samples by multiple devices to render A/V content [8].

For instance, in a demanding live audio performance, the microphone signal is streamed over a wireless channel to an audio mixing console where different incoming audio streams are mixed, and the in-ear audio mixes are streamed back to the microphone users via the wireless IEM system. For this, the audio sampling of microphones' signals must be perfectly synchronized to the system clock, which is usually integrated into the mixing console used for capturing, mixing, and playback of the audio signals. For immersive 3D audio effects, devices require synchronization accuracy of 1 ms, which is higher than the audio sampling clock [1, 8].

KEEPING DEVICES IN SYNC: EXISTING SOLUTIONS AND EMERGING REQUIREMENTS

The above studied use cases manifest that embedded shared understanding of time at devices is essential for cMTC applications. To use 5G therein, a synchronization solution over the 5G system is a key URLLC enabler. Apart from delivering the desired accuracy, it should support scenarios ranging from standalone operation to integration with existing/emerging solutions.

EXISTING INDUSTRIAL NETWORKS

Fragmented Legacy Solutions: In factory automation, the field devices — industrial devices and controller — are connected by various wired fieldbus and real-time Ethernet networks such as PROFIBUS, PROFINET, EtherCAT, Sercos, and Modbus. In power systems, the IEC 61850 series of standards specify networks for substation automation with profiles such as generic object-oriented substation event (GOOSE) and sampled values (SV). GOOSE is used for exchanging status, measurements, and interlocking signals between intel-

Critical industrial automation applications exhibit stringent requirements on communication latency and reliability, as well as on time-synchronized coordination among machines and robots.

Timing error source	Description	Typical values for SCS [15 30 60 120] kHz
Reference time indication errors		
Time alignment error	Refers to desired synchronization accuracy among BSs for perfect frame timing required by new NR technologies and services.	Tx diversity: ~ 65 ns
Reference time granularity	SIB16 granularity to transport reference time information.	250 ns
UE DL frame timing estimation	Detection error of DL signal at UE, and the device's processing jitter	[390 260 227 114] ns
TA related errors		
TA estimation error	TOA estimation is perturbed by measurement noise and multipath errors depending on the signal bandwidth and SNR of the direct path	Environment-dependent
TA granularity	Error introduced by limited TA granularity, $\pm 8 \cdot 64 \cdot T_c / 2^{14}$	[260 130 65 32.5] ns
TA adjustment error	Error at UE comprising systematic and dynamic factors.	[130 130 65 16] ns
Asymmetric DL/UL propagation delay	TA estimates UL propagation delay while reference time indication needs adjustment with DL propagation delay. Asymmetry in DL/UL propagation delay (FDD) will introduce inaccuracy in TA-compensated reference time.	Negligible in TDD
UE UL transmit timing error	The jitter in UL transmit time contributes to TOA estimation error, which could be considered to be negated by DL frame timing error.	Same as "UE DL frame timing estimation error"
Other errors		
UE modem to host interface chipset delay	Delay introduced by the interface between the device modem and the host chipset maintaining clock information.	~ 65 ns

Table 1. Timing errors associated with delivery of reference time from BS to devices [10].

ligent electrical devices (IEDs), while SV is used to transmit periodically sampled voltage and current measurements from measuring devices to IEDs [9]. The wireless solutions (e.g., WirelessHART, ISA 100.11a, WIA-PA, WIA-FA) constitute only a small fraction of the installed base and are used for non-critical connectivity of sensors over unlicensed bands.

Time-Sensitive Networking (TSN): The connectivity of industrial networks is expected to harmonize with the introduction of *Ethernet with TSN support* — an open standard being developed by IEEE 802.1 — where a TSN profile for industrial automation is being developed by International Electrotechnical Committee (IEC)/IEEE 60802. TSN includes the new features to standard Ethernet [3]:

- Deterministic and bounded latency without congestion loss
- Priority queuing with resource allocation
- Reliability with redundant flows
- Time synchronization among devices

Precision Time Protocol: Pertaining to the transport of precise time and synchronization in industrial applications, variants (profiles) of IEEE 1588 (PTP) protocol are used. For example, the PTP profile in TSN is IEEE 802.1AS, while the synchronization profile in IEC 61850 is IEC/IEEE 61850-9-3. However, synchronization is kept separate from the rest of the networking stack; thus, reliability and timeliness features are independent of any particular synchronization protocol.

5G SYNCHRONIZATION REQUIREMENTS

Timing Service in RAN: GPS could provide an accurate but costly solution to establish UTC time reference at devices. Further, jamming and weak signal reception raise concerns in indoor deployments. In indoor deployments, although a GPS antenna could be installed outdoors to enhance

signal reception, long feeder cable with an amplifier from the antenna to the receiver is required, which is costly and inflexible.

Consequently, there is an interest in built-in timing service over cellular networks. The 5G network can be considered stable and scalable; however, there is a need to upgrade the 5G air interface to distribute accurate time reference to the devices.

Unified 5G-TSN network: 5G is expected to satisfy most of the cMTC applications with new RAN features like faster scheduling, short/robust transmissions, faster retransmissions, preemption, and packet duplication, as well as diversity techniques. However, it will replace the existing systems in multiple phases, primarily driven by the benefits (cost, capabilities) of introducing 5G connectivity. Even in greenfield industrial deployments, not all industrial networks will be migrated to 5G. Therein, the 5G local industrial network will coexist with traditional networks and might even require transparent integration to transport industrial Ethernet or TSN. In such scenarios, collaborative actions of devices belonging to different domains need to be coordinated in time. Accordingly, the 5G system will need to relate/synchronize devices to a master clock of one or more time domains to enable time-scheduled coordination over a combined 5G-TSN network [11].

SYNCHRONIZATION IN 5G RAN

In this section, we study the 5G radio interface to transport reference time from the BS to the devices. Usually, a common notion of time can be maintained by periodically broadcasting time-stamps of reference time from master (i.e., BS) to slave devices. The devices use timestamp information to align their clocks after removing any time progress from the timestamping-to-reception

instance of the message [6]. The synchronization period depends on the frequency and phase stability of the onboard oscillators in devices, causing clock skew and drift. In this process, the main disrupting elements to synchronization accuracy are:

- *BS related*: time alignment error (TAE), time-stamping to transmission delay, and timestamping granularity
- *Channel related*: propagation time and its variations (jitter), asymmetry uplink/downlink propagation, and scheduling/medium access delays
- *Device related*: time adjustment errors at device, 5G device to IIoT host interface delay

In reference to a synchronization procedure currently being investigated in 3GPP Release 16, we discuss the following:

- Possible TAE at the BS
- Reference time indication procedure from the BS to devices
- Propagation delay adjustment in reference time

Table 1 summarizes the possible timing errors associated with these elements of the synchronization procedure.

TIME ALIGNMENT ERROR AT THE BS

Any TAE at the BS will add up to time uncertainty at the devices. The TAE requirements for new 5G technologies/services are summarized as follows [12]:

- *Tx diversity*: TAE of different transmitter branches at the BS is ± 65 ns.
- *New frame structure*: To avoid overlap in uplink and downlink timeslots in TDD systems, new 5G frame structure requires accuracy of ± 390 ns in D2B alignment.

REFERENCE TIME INDICATION

Reference time indication (RTI) is concerned with the distribution of reference time in 5G RAN from BS to devices. The reference time could be either the 5G or TSN network's clock. To distribute the 5G network clock as a reference, 3GPP considers 5G radio interface signaling as dedicated radio resource control (RRC) or system information block (SIB) broadcasts [13]. To support the distribution of the TSN clock, the 5G system acts as an IEEE 802.1AS time-aware system by adding TSN translators (TTs) in the wireless edge before a BS and after each device [14]. Only TTs support the IEEE 802.1AS operations; in particular, the timestamping of a PTP sync message at TTs using 5G clock and forwarding of the PTP sync via a user plane packet data unit (PDU). The difference in egress and ingress timestamps of a PTP sync message determines the *residence time* in the 5G system.

Hence, distribution of the 5G system clock is a prerequisite to establish any reference time at devices, while the following aspects of SIB/RRC signaling can introduce time uncertainty:

- *Time progression adjustment*: The BS needs to adjust the acquired reference time with a projected time of transmission: that is, up to a reference point in RTI frame occurring at the antenna reference point.
- *Granularity*: Timestamping granularity of SIB messages could introduce time uncertainty of up to 250 ns.

PROPAGATION DELAY COMPENSATION

Accurate estimation of propagation delay is a key factor to enable device-level synchronization. It is required to adjust the time progression after SIB timestamping/transmission. However, the need for propagation delay compensation depends on the service area. In the case of a small area (e.g., 10 m^2) the propagation delay is almost negligible (i.e., 0.3 ns), and the timing inaccuracy is the sum of reference time indication errors as listed in Table 1. For larger areas, 3GPP resort to utilizing timing advance (TA) in combination with SIB16. In LTE and 5G systems, TA is used to adjust the uplink transmission time of the devices based on their respective propagation delays in order to avoid collisions at the BS.

TA is negotiated during network access and RRC connected state using uplink reference signals: physical random access channel (PRACH), sounding reference signal (SRS), and demodulation reference signal (DMRS). During network access, the BS estimates TA from a *network access request* from a device and issues a TA command in *random access response* with N_{TA} value with index $T_A = 0, 1, 2, \dots, 3846$. The value of time alignment with subcarrier spacing (SCS) of $2^\mu \cdot 15 \text{ kHz}$ is a multiple of $T_\mu = 16 \cdot 64 \cdot T_c / 2^\mu$ s before the start of the corresponding downlink frame. Here, $\mu = 0, 1, 2, \dots$ defines the NR numerology, $T_c = 1/(480 \text{ kHz} \cdot 4096)$ is the 5G basic time unit. In RRC connected state, TA is negotiated with periodic control messages to adjust the uplink timing relative to current timing. The time alignment has the index value $T_A = 0, 1, \dots, 63$, which adjusts the current uplink timing by $(T_A - 31) \cdot T_\mu$ s.

As mentioned earlier, a device can use TA as an approximation of TOA — the propagation time from the device to the BS — in the absence of original TOA measurement. As each TA corresponds to a range of TOA measurements with a time slot $TS = T_\mu$ of limited granularity, TA can yield a maximum synchronization error of $\pm TS/2$. Moreover, the random errors in the original TOA could lead to wrong TA selection. The impact of random errors on TOA estimation from TA is further discussed later.

OTHER TIMING ERRORS

The above discussed radio parameters have other associated timing errors that must be considered in BS-to-device time offset budget to find synchronization inaccuracy. The components that could impact the accuracy are elaborated in Table 1 and can be logically visualized in Fig. 2.

ANALYSIS OF ERROR IN TIME OF ARRIVAL

We analyze the error in estimating TOA from TA while considering measurement errors in true TOA. A BS measures the unknown TOA of a radio signal with a certain random error, which is a function of signal bandwidth and signal-to-noise ratio (SNR) [15]. For TOA values within a timeslot, the BS assigns a TA value, which is the center of the timeslot as illustrated in Fig. 2. If TOA falls within one or two standard deviations (SDs) of the time slot center, there is a non-negligible probability that a wrong TA bin is selected. Selection of a wrong timeslot adds at least half of the time slot to the error in TOA.

Pertaining to the transport of precise time and synchronization in industrial applications, variants (profiles) of the IEEE 1588 (PTP) protocol are used.

For example, the PTP profile in TSN is IEEE 802.1AS, while the synchronization profile in IEC 61850 is IEC/IEEE 61850-9-3. However, synchronization is kept separated from the rest of the networking stack; thus, reliability and timeliness features are independent of any particular synchronization protocol.

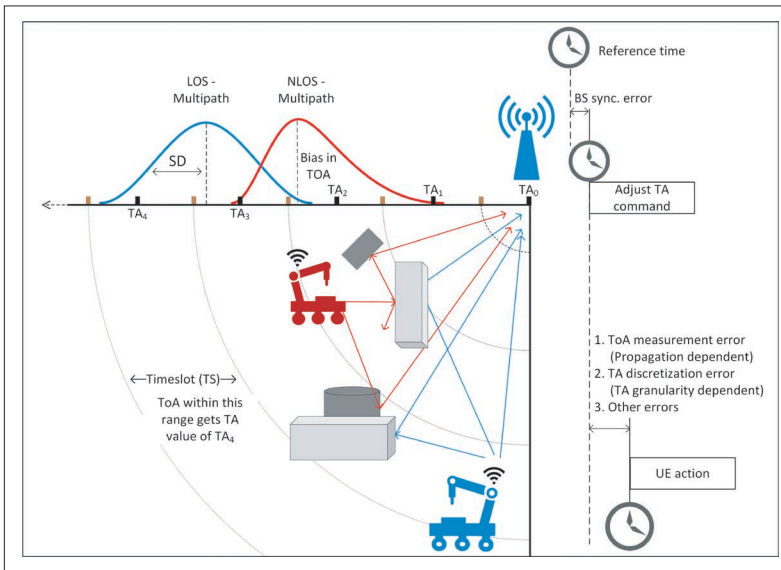


Figure 2. Transport of reference time information to the devices: principles and error components.

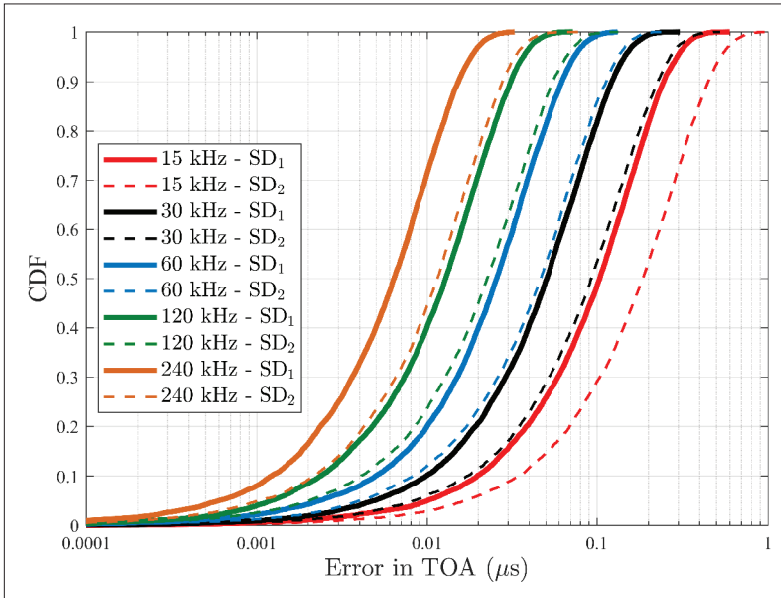


Figure 3. CDFs of the difference between true TOA and estimated TOA from reported TA, with $SD_1 = TS/2$ and $SD_2 = TS$ as the standard deviation (SD) of the measurement error in true TOA.

Thus, both the random error and the time slot width must be considered to find unknown TOA from TA.

We studied the error in true TOA and the estimated TOA extracted from reported TA by simulations. We assume a uniform distribution of true TOA in a time slot, where true TOA is perturbed by unbiased Gaussian errors, while standard deviation is set as a function of time slot width. It implies that the effect of random errors reduces with the increase in SCS; a receiver's ability to resolve TOA of multipath signal components improves with increase in subcarrier spacing. Figure 3 shows the cumulative distribution functions (CDFs) of the error in TOA for different SCSs. The CDF curves are useful to define the confidence level in synchronization accuracy when adjusting the propagation delay in reference time indication. The maximum error in TOA, which satisfies the condition that the

error remains less than that with probability of one, must be used in the device synchronization budget. It can be observed that as SCS increases, the estimation error in TOA reduces. Note that if the timing errors in Table 1 are taken into account, the error for SCS of 15 kHz is high enough not to satisfy the 1 μ s target.

One solution to reduce the TOA estimation error is to take an average of two or more consecutive TAs. The averaging reduces the error caused by the TOA measurements that are assigned TA values to the sides of true TA. For SCS 15 kHz, Fig. 4 shows that error reduction obtained by averaging multiple consecutive TAs is substantial. Therefore, a required synchronization accuracy target can be achieved by appropriate selection of averaging size for a given measurement random error, which is influenced by the propagation conditions.

Random error under multipath fading: Figure 3 shows that TOA estimation from TA depends on the amount of perturbation in true TOA. In densely cluttered environments, the true TOA is perturbed by both the measurement noise and line-of-sight (LoS)/non-LoS (NLoS) multipath error. In LoS multipath environments, multipath signals tend to arrive close to the direct path. The signals combine to create a cluster in the power delay profile, making it challenging to extract TOA of the direct path. As a result, depending on the structure of the propagation environment, TOA estimation from TA may lead to varying synchronization errors. The statistics of LoS multipath errors can be modeled as zero-mean Gaussian with variance directly related to the variations in the multipath structure [15].

On the contrary, the NLoS multipath environment is challenging because of multipath errors, where the TOA estimation depends on the detection of a direct path (DP). If the attenuated DP is detectable (consider light obstructions), better TOA estimation can be achieved. On the other hand, if the DP is buried in noise, it will create a bias (Fig. 2) toward a longer first non-DP. Since shadowing introduces fluctuations in the detection of the first arrival path, the variance of multipath error is also time varying. Clearly, NLoS introduces bias as well as other perturbations in TOA estimation. One technique to remove bias could be to introduce an average correction for it. The asymmetric distribution of random errors may even require a TOA estimator other than the time slot center.

CONCLUSIONS AND RESEARCH DIRECTIONS

Sharing a common time base among devices is essential for cMTC applications to perform various tasks ranging from coordination, sampling, and fusion to event reconstruction. Together with low latency and ultra-reliability, enabling ultra-tight time synchronization can be regarded as the third dimension of 5G RAN enhancements. To operate either in standalone or in cohesion with TSN/Ethernet solutions, transport of reference time over the 5G air interface is currently being investigated in 3GPP Release 16 in order to enable device-level synchronization across multiple domains. In this article, we discuss enabling radio parameters in 5G NR and focus on propagation time compensation in reference time based on timing advance. Timing advance corresponds to a set of TOA values, which is perturbed by signal propagation

conditions and could lead to substantial errors in time synchronization. We studied the TA-dependent timing error and observed that the averaging of multiple TAs could reduce the error and satisfy the overall accuracy target. Nevertheless, there are still many research areas to be addressed, for instance:

- Impact of mobility on TA averaging
- TOA uplink and downlink asymmetry
- Bias and TOA error asymmetry in NLoS conditions

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BIOGRAPHIES

AAMIR MAHMOOD [M'18, SM'19] (aamir.mahmood@miun.se) is an assistant professor of communication engineering at Mid Sweden University. He received his M.Sc. and D.Sc. degrees in communications engineering from Aalto University School of Electrical Engineering, Finland, in 2008 and 2014, respectively. He was a research intern at Nokia Research Center, Finland, and a visiting researcher at Aalto University during 2014–2016. He served as Publications Chair of IEEE WFCS 2019. His research interests include network time synchronization, resource allocation for URLLC, and RF interference/coexistence management.

MUHAMMAD IKRAM ASHRAF (ikram.ashraf@ericsson.com) is an experienced researcher in network architecture and protocols at Ericsson Research, Jorvas, Finland. He joined Ericsson in 2018 and mainly works on industrial wireless communication with a

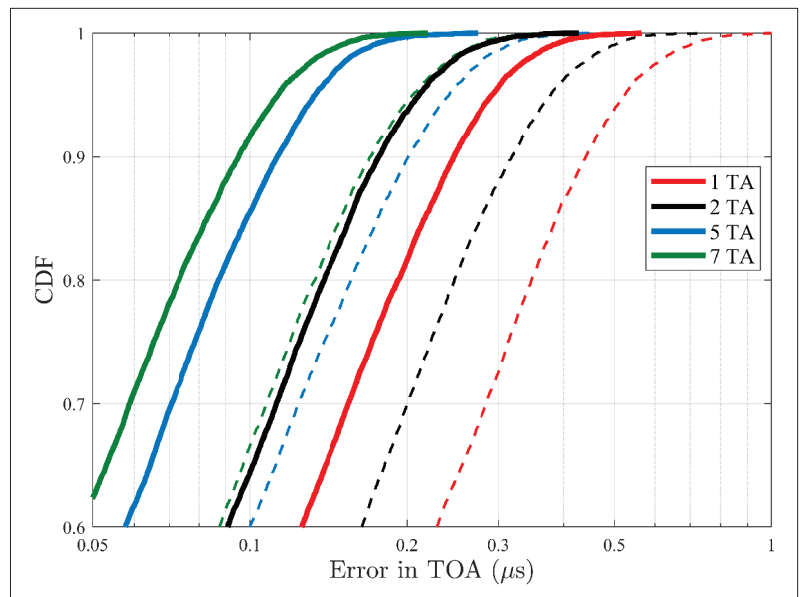


Figure 4. Error reduction by averaging multiple TAs for 15 kHz subcarrier spacing. Solid curves: $SD = TS/2$, dashed curves: $SD = TS$.

focus on URLLC. Before joining Ericsson, he worked for Nokia Bell-Labs and Centre for Wireless Communication (CWC) at the University of Oulu, Finland. He has authored/co-authored more than 30 international scientific publications and has contributed to several standardizations. His current research interests include 5G radio networks, Industrial IoT, TSN, and V2X communication.

MIKAEL GIDLUND [M'98, SM'16] (mikael.gidlund@miun.se) is a professor of computer engineering at Mid Sweden University. He has worked as senior principal scientist and global research area coordinator of Wireless Technologies, ABB Corporate Research, Sweden, a project manager and senior specialist with Nera Networks AS, Norway, and a research engineer and project manager with Acreo AB, Sweden. His current research interests include wireless communication and networks, wireless sensor networks, access protocols, and security. He holds more than 20 patents in the area of wireless communication. He is an Associate Editor of *IEEE Transactions on Industrial Informatics*.

JOHAN TORSNER (johan.torsner@ericsson.com) is a research manager at Ericsson Research and is currently leading Ericsson's research activities in Finland. He joined Ericsson in 1998 and has held several positions within research and R&D. He has been deeply involved in the development and standardization of 3G and 4G systems and has filed over 100 patent applications. His current research interests include 4G evolution, 5G, and machine-type communication.

JOACHIM SACHS (joachim.sachs@ericsson.com) joined Ericsson Research in 1997 and currently holds the position of principal researcher in network architectures and protocols. He has contributed to the development and evaluation of 3G and 4G, and today coordinates the research and standardization activities on machine-type communication and URLLC for 5G. He holds a diploma in electrical engineering from Aachen University and a doctorate in electrical engineering from the Technical University of Berlin, Germany. Since 1995, he has been active in the IEEE and the German VDE Information Technology Society (ITG), where he is currently Co-Chair of the Technical Committee on Communication.