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Phase and Time Synchronization for 5G C-RAN: Requirements, Design Challenges and Recent Advances in Standardization

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Abstract

Cloud-RAN is one of the key enablers for 5G. In this paper we present the importance of network synchronization for the fronthaul architectures. The term network synchronization refers to the distribution of time and frequency among spatially distributed remote nodes. Underlining this point, we investigate the requirements and network design challenges to precisely synchronize the 5G C-RAN radio units. We conclude the article by pointing-out the recent advances in standardization together with describing the proposed practical solutions and methodologies to practically overcome these challenges in real networks.

Keywords: C-RAN Architectures; Transport Networks; Network Synchronization; Design Challenges.

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1. Introduction

Cloud RAN or Centralized RAN (C-Radio Access Network) is an architecture in which the base band processing unit (BBU) is decoupled from the radio resource unit/head (RRU/RRH) and it is centralized. The transport network that connects the BBU and the RRH is termed as Fronthaul (FH). Moving towards 5G, a key break-through for C-RAN is the ability to flexibly split the RAN functions between the BBUs and RRHs, now termed as the Centralized Units (CUs) and the Distributed Units (DUs) and Radio Units (RUs) respectively. This allows centralizing only a portion of the baseband functions and distributing the rest of the RAN functions at the cell site. This flexibility allows network operators to deploy different functional split options of C-RAN architecture in their networks driven by the different end-user requirements. Despite such high appeal, among others, a key obstacle that remains open today towards the successful massive deployment of 5G C-RAN architecture in commercial operator networks is related to ***network synchronization***.

1.1. Significance of this article and discussions here-in

Centering on this key issue, in this article we present our views on the requirements and network design challenges to precisely synchronize 5G C-RAN radio units. Here onwards, we present the evolution of the FH transport architectures and describe the various the FH transport solutions for synchronization, developed by different standard bodies (***detailed in Section 2***). We then explain how the radio performance is highly dependent on the FH synchronization. We analyse the FH transport requirements based on the accuracy levels of various emerging radio features (***detailed in Section 3***). The discussions ultimately lead to answer the question, "How to precisely synchronize the future C-RAN radio units and what is the impact of synchronization on C-RAN architectures?" (***detailed in Section 4***). The scenarios and use-case applications handled in this article are non-exhaustive. Needless to say, our aim is that this article could fill-in as direct reference to address the requirements and the challenges associated to properly design a network in order to precisely synchronize and distribute time across it.

2. Towards a flexible C-RAN Architecture

2.1. From Research to Standards

In the context of flexible C-RAN, several research works focussed on how to split the RAN functions flexibly [1]-[3]. As a consequence, several standards development organization (SDOs) such as 3GPP RAN3, IEEE NGFI (1914) Working Group went on to investigate the various RAN functional split options [4], [5] that could be possibly deployed in operational networks, represented in figure 1(b).

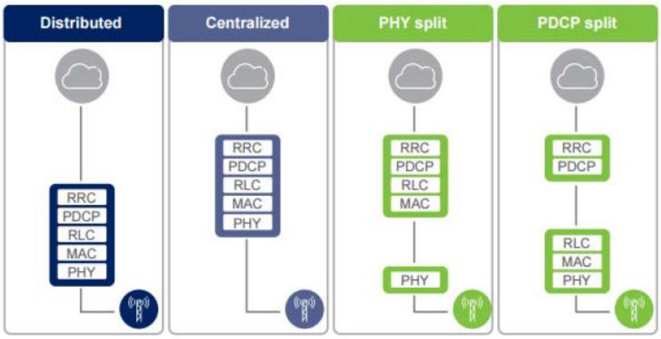


Figure 1(a). Illustration of functional block diagram of a classical eNodeB/RAN architecture where all of the RAN functions are centralized/distributed in one location, typically in the cell site.

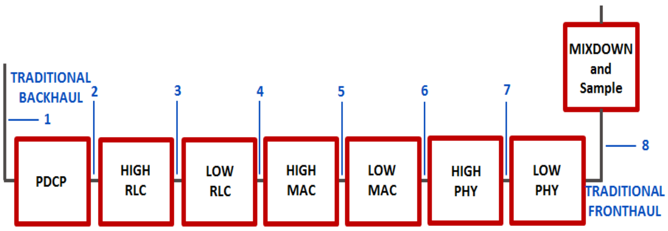


Figure 1(b). Illustration of different RAN functional split options from 3GPP TR-38.801, Release 14.

From a transport network point of view, the current FH transport is represented by Common Public Radio Interface (CPRI); it connects the BBU and the RRH. However with regards to 5G, Ethernet-based FH transport is pushed strongly by operators. It is due to the existing limitations in CPRI to support 5G data rate, as well as due to the presence of Ethernet equipment in operator transport networks. Nevertheless, there are still challenges to tackle with Ethernet in the FH, as pointed-out in [6],[7]. Among others, one undisputed challenge is to transport and distribute phase/time synchronization through the FH transport in order to precisely synchronize the C-RAN radio units. In contrast to CPRI, Ethernet does not transport synchronization. Focusing on this problem, in this article we present the challenges and solutions to precisely time synchronize flexible C-RAN radio units via FH transport.

2.2. On the role of network synchronization

Network synchronization or time distribution is relatively an overlooked field of research; yet its importance is growing at an exponential rate. Today several SDOs play an active role to develop synchronization solutions for telecom networks. Notably 3GPP RAN3, ITU-T SG15/Q13 (Study Group 15-Question 13), IEEE 802.1 TSN (Time Sensitive Networking Group), and the IEEE 1588 Group are the key players. In particular 3GPP and ITU-T are major drivers for developing synchronization requirements, solutions and architectures for cellular networks. While 3GPP defines the fundamental synchronization requirements, ITU-T develops solutions and architectures for these requirements. ITU-T defines synchronization as the process of delivering a 'common reference' to the cellular base stations from a common source within a given accuracy and stability. The ITU-T has standardized Synchronous Ethernet (SyncE) technology [8] and Precise time Protocol version 2 (PTPv2) [9] to synchronize the existing 3G, 4G mobile base stations. For the sake of brevity, we do not get into the technical details of these solutions.

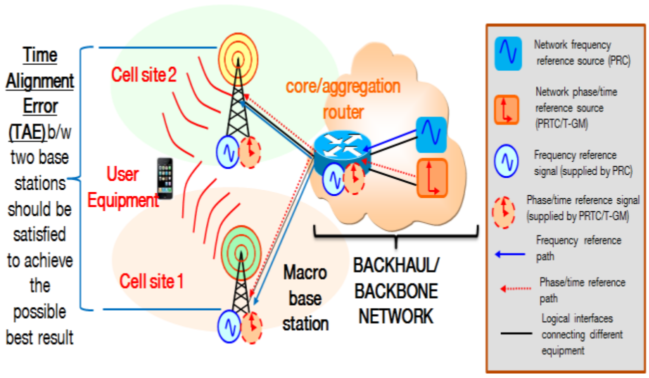


Figure 2. Illustration of synchronizing two wireless base station, where Time Alignment Error (TAE) between two base stations is crucial to obtain the best radio performance.

Figure 2 represents a typical mobile network architecture indicating the delivery of frequency and time/phase over-to the end base station from the backhaul. In the above figure it is hard to ignore the time alignment error (TAE) between two adjacent base stations. In practice, accurate synchronization improves the radio performance over-the-air which is directly related to the TAE. From a design perspective, base stations are equipped with Local Oscillators (LOs), be it any generation of wireless mobile telecommunications technology i.e. 3G, 4G, etc. From a deployment perspective, these LOs must be locked to a particular reference frequency at a given time, in order for the base stations to be precisely synchronised to each other. Over the period of time, the accuracy levels with which these LOs must be locked has evolved. In particular in the context of 5G, the accuracy values are immensely stringent.

3. Challenges to Synchronize C-RAN FH

3.1. Impact of Radio over Ethernet (RoE) on FH transport

While analysing synchronization requirements from FH transport perspective, the existing standardized solutions and methods do not vary, i.e. SyncE and PTPv2 are still valid solutions. Figure 3 represents the transport of frequency (SyncE) and phase/time (PTPv2) synchronization over Ethernet-based FH transport, under the assumption that the future FH transport networks in 5G would be very likely based on Ethernet. In our earlier article [13], we have already analysed synchronization over optical transport networks.

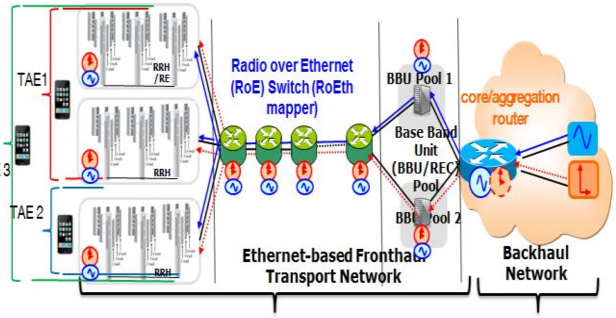


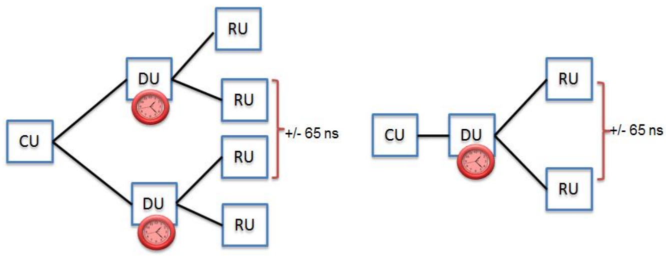
Figure 3. Illustration of transport of frequency and phase/time synchronization over fronthaul network.

Here the fundamental limitation for synchronization is that, with active equipment (i.e. Ethernet) placed in the FH, the transport of synchronization over the FH necessitates that each active equipment supports SyncE and PTPv2 functions. This is because when CPRI is transported over Ethernet, CPRI losses its native synchronization capabilities which are inherently present in it. Nevertheless even when SyncE and PTPv2 are supported in the FH transport network, there are still transport network design considerations that are challenged. Particularly while analyzing the transport of radio (CPRI) over the Ethernet, it gets more complicated. So from a high level, the fundamental protocol requirements for synchronization would remain the same. But transporting radio (CPRI) over Ethernet complicates synchronization aspects. When CPRI is embedded into an Ethernet stream (Radio over Ethernet (RoE)), the CPRI reference clock will be used to manipulate the Ethernet reference, so that firstly the Ethernet channel can be frequency locked to a particular selected CPRI feed using the CPRI timing channel. Once it is frequency locked, then PTPv2 solution could be used to lock in phase and time. However, in a commercial network when radio is transported over Ethernet along with other traffic types, there are still several problems to solve today, namely how to encapsulate and map radio over Ethernet, how and when to prioritize different types of traffic including synchronization traffic through FH etc. While there are several emerging IEEE standards to deal with the transport of Radio-over-Ethernet, such as the newly formed NGFI IEEE 1914.1 project (Standard for Packet-based Fronthaul Transport Networks), the IEEE P1914.3 (Standard for Radio Over Ethernet Encapsulations and Mappings), the IEEE 802.1CM-Time Sensitive Networking for Fronthaul, at the time of writing this article none of them had provided a completed standardized solution for operators.

3.2. Impact of radio performance requirements on FH

Moving forward, in this section we analyze FH transport requirements based on the accuracy levels of various emerging radio features, summarized in Table I. From the Table 1, Scenario ❶ ❷and ❸could be grouped together and the scenario ❹ is separated, from a timing perspective. The additional performance requirements from the FH transport networks, coupled with more stringent performance requirements for new RAN features beyond 4G (detailed in Table 1) imposes additional constraints on synchronization performance when applied to the FH transport. In theory, precise synchronization improves the radio performance over-the-air which is directly related to the time alignment error (TAE) between two adjacent base stations. As a result, it goes without saying that in C-RAN architecture, the RUs which are not precisely synchronized would result in the carrier frequency variations which in turn would result in random phase noise. This directly results in poor radio performance at the air interface.

Scenario ❶, ❷ and ❸: These three scenarios represent Class A+, A and B category of service classes defined by CPRI group respectively. The corresponding use case applications defined by 3GPP are also pointed-out in Table 1. While observing Table 1, the most stringent TAE between base station antenna ports (i.e. between different RUs) is fixed for the use-case application *MIMO or TX diversity transmission*, as ±65 ns. Similar values could be seen for Class A and B as well. For the time-being, let's focus only on Class A+ for our analysis.



(a) (b)

Figure 4. Illustration of relative time error alignment when RUs are connected to diferent DUs (a) and to the same DU (b) in the context of 5G use cases.

Looking at Table 1, we observe also that the IEEE 802.1CM project has defined the maximum absolute time error between multiple antenna ports, since Class A+ is a service class which is based on multiple antenna coordination. For Category A+ it is limited to 12.5 ns with respect to the last common point (i.e. here it refers to the DU to which multiple RUs connected). And this means when an operator wants to deploy Class A+ service in a commercial network, in addition to guaranteeing the +/- 65 ns between multiple RUs, it is also equally important to make sure that TAE between base stations antenna ports with respect to the last common DU is restricted to 12.5 ns (or approximated to 10 ns). The key to this is that, this measurement is between antenna ports, which typically for MIMO or TX diversity will be on a single DU. But in the context of 5G, contrary to what is described above, it is currently foreseen to synchronize different RUs from different DUs (or even different CUs) [12]. This is illustrated in figure 3. Here if the timing error of the slave clock in the RU is compared to the last common time source (i.e. if different DUs is considered as the reference point in the place of a common CU), then in a commercial network, it may be close to impossible to deploy Class A+ service. Another key aspect here is also to determine where the time source (UTC) is placed. If the time source is placed at the last common CU, then the relative time error between multiple RUs is the same as the relative time error between multiple DUs. But if the time source is placed only at the DUs, then it is impossible to obtain +/- 65 ns between different RUs.

Table 1. Illustration of Phase/Time Synchronization Timing Error Magnitude for the Fronthaul

Scenarios	Class (as defined by CPRI)	Use case/ Applications developed and defined by 3GPP	Magnitude of absolute time error between adjacent base stations relative to UTC, defined by 3GPP for specific applications	Magnitude of relative time error between base stations	Internal Timing Error budget consumed by the end Radio Equipment as specified by CPRI	Maximum Absolute Timing Error with respect to a common point in the sync chain defined by IEEE 802.1CM
❶	A+	MIMO & TX diversity	±65 ns	32.5 ns	20 ns	12.5 (~10) ns (TAE with respect to the last common PTP equipment.)
❷	A	Intraband contiguous carrier aggregation	±130 ns	65 ns	20 ns	45 ns (TAE with respect to the last common PTP equipment.)
❸	B	Intraband non-contiguous and interband carrier aggregation	± 260 ns	130 ns	20 ns	110 ns (TAE with respect to the last common PTP equipment.)
❹	C	Time-Division Duplex	±1500 ns	1500 ns	20 ns	1360 ns (TAE with respect to the last common PTP source/generator where 100ns consumed by the PTP source.)

Similarly Class A and B services represent the carrier aggregation feature. By combining two or more component carriers in the same or different frequency bands, network operators increase the transmission bandwidth and thereby the end-user throughput is eventually improved. From a timing and sync perspective, when operators want to combine the same frequency band (from the same or multiple eNodeBs), operators must make sure that the TAE between these carriers is very small. When multiple coordinating cells are not accurately synchronized, the combining carriers from the same frequency band will exhibit interference and hence the radio performance decreases.

From Table 1, it is therefore evident to understand why the TAE of Intraband contiguous carrier aggregation is much smaller than the TAE of Intraband non-contiguous carrier aggregation. Again, similar to Class A+ service, the TAE values for Class A and B are defined with respect to the last common PTP equipment and not the last common PTP source (represented as 45 ns and 110 ns respectively).

Scenario❹: Scenario 4 represents Class C where the timing error of the slave clock in the RU, DU or CU is compared to any common time source and not the last common PTP equipment, i.e. it must be traceable to Coordinated Universal Time (UTC). One fundamental reason to synchronize TDD systems is to avoid interference without losing spectrum in guard bands. In a TDD system, signals are transmitted and received on the same frequency band. When more than one TDD network operate in the same zone and in the same band, strong interferences occurs if the networks do not coordinate because downlink and uplink timeslots overlap i.e. if one TDD base station transmits while other base stations receives, both using the same frequency.

This is true especially for collocated macrocells operating on adjacent channels due to imperfect adjacent channel selectivity on the receiver side and out-of-band emission on the transmitter side. This will block the neighbor receiver, forbidding the receiver from accurately listening to the signals from end-user terminals. In case of FDD-TDD coexistence, this issue is eliminated by the use of guard bands. However in the case of TDD-TDD coexistence, phase/time synchronization is the only way to avoid this issue without losing spectrum.

3.3. Impact of flexible functional splits on FH

Adding to this, the various fronthaul functional splits proposed/or under implementation by different SDOs (please revisit figure 1(b)) dictate additional impact on FH transport, which includes transporting synchronization packets as well. In general terms, any modification to the RAN functional split will not introduce any additional synchronization challenges in terms of the solutions and methods recommended (i.e. SyncE and PTPv2 are still valid solutions). But when a RAN is functionally split, it imposes a certain level of constraint on the synchronization accuracy level. That is, when the RAN is functional split, it gives the flexibility to network operators to deploy a particular functional split option in their network driven by a particular end-user requirement.

Hence different functional split options are developed to satisfy different constraints. Lower layer functional splits are more suitable for (radio) applications which necessitate low bandwidth and could tolerate high latency. Higher layer functional splits are more suitable for (radio) applications which require high bandwidth and could tolerate low latency. For instance, option 2 which is a higher layer functional split option enables Class A+ type of applications such as MIMO & Tx diversity since sampled waveforms are no longer transported and instead intermediate signals are serialized and then transmitted as packets over Ethernet. Therefore this requires that more processing is moved from the DU to the RU with the aim of reducing the bit-rate and enabling statistical multiplexing gains with other traffic over the same Ethernet links. On the other hand, option 7 which is a lower layer split, the whole waveform has to be transmitted when transporting digitized waveforms, even if a user is receiving little or no data resulting in much higher, constant data rates being transmitted in the fronthaul.

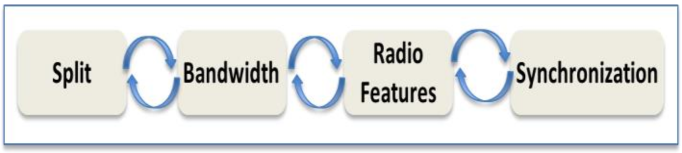


Figure 5. Illustration of the impact of functional splits over synchronization

Now looking at Table 1, it is clear that a particular synchronization requirement is allocated to a particular class of service. Thus one could deduce that each functional split influences a unique bandwidth gain over the FH transport. These bandwidth gains enable specific radio features to be deployed in commercial networks, which necessitates a particular level of synchronization. This in turn has an impact on air-interface performances. Therefore, when a network operator chooses to roll-out a particular radio feature in a commercial network, it is not only enough to design a proper FH transport network, but also equally important to supply the exact synchronization accuracy together with choosing the appropriate functional split. This is illustrated in figure 4.

4. Network Design to Precise Synchronization

All through this article we have pointed-out the challenges and limitations to synchronize the C-RAN RUs. As described so far, in the context of 5G, since part of the RAN is moved to the transport, the FH transport network design relies on the radio network performance. Therefore, in the section below, we propose novel solutions and describe the methodologies to practically overcome these challenges in real networks from timing and synchronization perspective.

4.1. Phase Alignment

From a design perspective, base stations are equipped with Local Oscillators (LOs), be it any generation of wireless mobile telecommunications technology i.e. 3G, 4G, etc. These LOs must be locked to a particular reference frequency at a given time, in order for the base stations to be precisely synchronised to each other. The accuracy levels with which these LOs must be locked has evolved from 3G to 4G and from 4G to 5G now. These LOs are present in each individual RU. Continuous carrier frequencies are generated by these LOs. They must conform to requirements defined by radio standards. For instance, in 4G-LTE OFDM-based system, the permitted CFO is between 50 ppb and 250 ppb for different types of base station, i.e. macrocell base station, small cell base station etc. [10]. When multiple carrier signals from multiple RUs are combined, they result in a compound signal. This requires coordination between multiple RUs' carrier signals and this is done by precisely and accurately synchronizing the individual RU. Such coordination results in advanced features such as carrier aggregation or joint MIMO transmissions. Inversely, when the carrier frequencies between multiple RUs are uncoordinated, they result in poor radio performance.

Carrier Frequency Offset (CFO) is caused as a result of mismatch in carrier frequency from the LOs at the transmitter side. This causes a phase shift at the receiver side, resulting in loss of orthogonality. In theory, OFDM systems estimate CFO in time domain. This is done through repetition pattern, i.e. by repeating the primary synchronization signal (PSS), preamble, training sequence, cyclic prefix (CP)) and therefore could estimate and correct the carrier frequency phase shift of the LO. However, in the context of 5G, several non-orthogonal, asynchronous waveform transmissions (such as GFDM, UFMC and FBMC) are proposed. This non-orthogonality of the 5G system necessitates CFO measurement in frequency domain. One way to estimate CFO in frequency domain is by dispersing the RF sub-carriers in time domain and measuring the phase differences of sub-carriers between two repeated patterns. The net effect of the change in carrier frequency gives the phase rotation of received patterns. This enables to adjust the relative phases between the RF channels and compensate any time delays between them and therefore estimate the CFO in frequency domain.

But now the question is what role does the FH transport plays in estimating and correcting CFO in order to synchronize the RUs, so that the channel capacity of the entire system is improved. As stated before, each individual RU transmits a carrier frequency signal. It is possible to phase align the carrier frequencies of several individual RUs. However, in the case of massive MIMO (antenna scaling more than 64), rather than absolute phase alignment, a consistent phase coherency is enough to maintain the expected radio performance. This is because when multiple RUs coordinate in massive MIMO systems, the random phase is also processed together with the RF channels. Therefore, it is enough that the varying spatial dimensions between multiple RUs remain with a consistent phase relationship to each other, instead of absolute phase alignment. This phase relationship can be exploited and thus several data streams from different RUs can be spatially multiplexed onto the RF channel to increase the channel capacity of the massive MIMO system. In this regard, there are certain measures to be taken for reconstructing phase coherency at the RU side. From a FH design perspective, the role of LO embedded in each RU is significant in order for a consistent phase coherency.

There are two ways to reconstruct phase coherency at the RU side: (i) either a single time reference source (reference clock) is divided and distributed among all the channels of the MIMO system. Here each individual channel would synthesize its own LO signal or (ii) a single LO signal is directly divided and distributed amongst all the RF channels. In the former case when a single source is shared among all the RF channels, separate individual PLLs are used in every channel to synthesize the LO signal of that channel. The downside of this is that, each RF channel generates a phase noise, due to the PLL present in it. The phase noise of one RF channel is different from the phase noise of another. As a result of this, the mean phase difference between each RF channel could not be accurately calibrated. Therefore the phase relationship between each RF channel could not be established. The latter case is when a single LO is directly divided and distributed amongst all the RF channels. Here the PLL of a single RF channel is used to synthesize all the other channels of the MIMO system. Thus all the RF channels of MIMO system receive the same LO signal. Therefore, all the channels will experience the same instantaneous phase noise. The result of this is that, on every channel the instantaneous phase change due to phase noise is the same, and therefore aligned in phase. From a FH transport perspective, RUs must generate continuous carrier waves. Atomic oscillators such as Cesium-based oscillators or Rubidium-based oscillators used in most legacy base stations could be used to generate such frequencies. However, directly deploying such oscillators on the RUs would increase the cost of RU equipment for operators, particularly in the context of 5G where massive number of antennas and RF equipment are foreseen. Therefore, such oscillators must be deployed in the CUs (or DUs) and this frequency must be transported over-to the RUs with the support of SyncE in the FH transport.

4.2. Time Alignment

Moving forward, while transporting data through the FH network, we transport I/Q modulated signals in place of continuous carrier frequency. In this case, the baseband signal must be aligned in time in addition to phase alignment. Since I/Q modulated signals are digitalized signals, any misalignment in frames is prevented by time synchronization. From a transport network point of view, there are two ways to time align the I/Q modulated signals in the FH (i) recover frequency and then time-align using Clock and Data Recovery (CDR) mechanism (ii) recover timing from the BBU directly.

The first one is the use of Clock and Data Recovery (CDR) mechanism. CDR is a process in which the receiver (here it refers to the RU) generates a clock from an approximate frequency reference (received from the CU or DU) and then phase-aligns the clock to the transitions in the data stream with a phase-locked loop (PLL). The downside of this mechanism is that it would result in downlink jitter. Consequently, downlink jitter has to be limited in such FH interfaces (maximum jitter permitted in CPRI is 8.138 ns), because any deviation in the bit clock impacts the recovered frequencies [11], which impacts the time alignment, which in turn affects the time/phase synchronization. To limit the downlink jitter, the data must be transported with minimal Packet Delay Variation (PDV) over the FH so that the transport of inflow bits used for CDR is synchronous.

The second case is to recover the time from the BBU directly. In order to do this, all the transport equipment in FH must be embedded with time transfer protocol functionality such as PTPv2. This enables tight synchronization. So now when an RU has PTPv2 function, it is naturally embedded with a real-time clock (RTC).This supplies the time-of-day (ToD) information. In this case, the ToD information would enable the RUs to synthesize precisely to the synchronized frequencies; thereby the problem of PDV is avoided. Then it could phase-align the clocks, thereby allowing it to synchronize in phase/time with other RUs. In cases when the CU (or DU) unit has a very precise time reference, then the RUs could lock to the CU (or DU) and then the locally generated frequencies can inherit the phase/time accuracy from CU (or DU). In this scenario, if queuing and forwarding buffers of the transport equipment in the FH are properly configured to withstand the inter-arrival intervals then PDV is not much of a concern for radio traffic. On the contrary, the PDV could become problematic to the PTP accuracy. This can be mitigated by techniques such as prioritization of the PTP traffic over radio traffic, decreasing the number of transport nodes in FH etc.

5. Conclusion

5G is on its way and C-RAN architectures are extensively considered as part of 5G eco-system. While the research community focusses on inventing new radio advanced features, operators' requirements to deploy those features are not always fulfilled from a practical point of view. Among other areas, network synchronization is an obscured field of research. Persuaded by the requirements and the necessity faced by operators today to deploy emerging and advanced radio access features and technologies, in this article we presented the requirements and challenges linked to the introduction of phase and time synchronization in FH transport. We analyzed the FH transport requirements based on the accuracy levels of various emerging radio features. We have also analyzed the recent advances in standardization and we have proposed novel solutions and methodologies to practically overcome these challenges in real networks.

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