# Round Trip Time Estimation Utilizing Cyclic Shift of Uplink Reference Signal

Rajeev Gangula\*, Tommaso Melodia\*, Rakesh Mundlamuri\*<sup>†</sup>, and Florian Kaltenberger\*<sup>†</sup>

<sup>†</sup>Communication Systems Department, EURECOM, Biot, France

\*Institute for the Wireless Internet of Things, Northeastern University, Boston, USA

Abstract—In the context of fifth-generation new radio (5G NR) technology, it is not possible to directly obtain an absolute uplink (UL) channel impulse response (CIR) at the base station (gNB) from a user equipment (UE). The UL CIR obtained through the sounding reference signal (SRS) is always time-shifted by the timing advance (TA) applied at the UE. The TA is crucial for maintaining UL synchronization, and transmitting SRS without applying the TA will result in interference. In this work, we propose a new method to obtain absolute UL CIR from a UE and then use it to estimate the round trip time (RTT) at the gNB. This method requires enhancing the current 5G protocol stack with a new Zadoff-Chu (ZC) based wideband uplink reference signal (URS). Capitalizing on the cyclic shift property of the URS sequence, we can obtain the RTT with a significant reduction in overhead and latency compared to existing schemes. The proposed method is experimentally validated using a real-world testbed based on OpenAirInterface (OAI).

#### I. INTRODUCTION

Apart from offering high data rates and low latency communication, next-generation networks are expected to provide precise positioning and environment sensing capabilities [1], [2]. The third generation partnership project (3GPP) has defined several positioning methods and procedures in the fifthgeneration new radio (5G NR) technology and expected to enhance them in the future releases, with sixth-generation (6G) standardization starting from the year 2025 [3]. Timing-based positioning methods in 5G include downlink time difference of arrival (DL-TDoA), uplink time difference of arrival (UL-TDoA), and multi-cell round trip time (multi-RTT) [4], [5].

The multi-RTT positioning method involves estimating a user equipment's (UE's) location using the round trip time (RTT) between the UE and multiple base stations (gNBs). The UE's 2D position can be estimated with the RTT from at least three well-placed gNBs using the trilateration procedure. Unlike the TDoA method, very tight (order of nanoseconds) synchronization among gNBs is not required in RTT methods. The 3GPP has defined the following RTT-based positioning methods: enhanced cell ID (ECID) type I & II and multi-RTT [4]–[10].

Despite being standardized, the performance evaluation of the 3GPP-compliant positioning methods has traditionally been limited to either system-level simulations or real-world experimental evaluations in proprietary settings [4], [5], [11], [12]. However, with the success and wide adoption of opensource 5G reference implementations such as OpenAirInterface (OAI), it is now possible for researchers to validate their positioning algorithms with real-world experiments. Few works have demonstrated the timing-based 5G positioning techniques in real-world experiments using the OAI platform [13]–[18]. While the work in [17] is based on RTT, the works in [13]–[16] focus on DL-TDOA and UL-TDOA methods.

This work introduces a new RTT estimation scheme for 6G systems. The proposed method enhances the current 5G protocol stack with a new uplink reference signal (URS), and significantly reduces the overhead and latency in obtaining the RTT compared to existing schemes in the literature and 3GPP standards [4]–[10], [17]. Specifically, our contributions are

- A new reference signal, URS, similar to the sounding reference signal (SRS) in 5G is introduced that allows us to estimate the RTT at the gNB
- The OAI gNB and UE protocol stack is updated with the URS feature
- The proposed RTT method is then validated with overthe-air experiments
- The framework allows us to jointly estimate the RTT from multiple URS measurements, resulting in better performance in low signal-to-noise ratio (SNR) scenarios.

We now proceed with the background that lays down the basis to understand the state-of-the-art RTT methods and the novelty of the proposed scheme.

# II. BACKGROUND

This section provides a brief overview of the tools and procedures necessary for RTT measurement in 5G NR.

#### A. 5G Synchronization

In 5G NR, the synchronization process consists of downlink (DL) and uplink (UL) synchronization. The DL synchronization is achieved by UE acquiring the frame and symbol boundary by decoding the synchronization signal block (SSB) transmitted by the gNB. The UE can then decode the master information block (MIB) from the physical broadcast channel (PBCH) and system information block (SIB) from the physical downlink shared channel (PDSCH). The parameters extracted

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Figure 1. RTT estimation with RACH



Figure 2. UL timing adjustment at UE

from the MIB and SIB are necessary to perform UL synchronization.

The gNB handles multiple UE's situated at different distances across the cell. Therefore, each UE's UL transmission time needs to be adjusted to align with the gNB's UL reception. UL synchronization is achieved through a combination of the random access (RA) procedure and timing advance (TA) loops. The RA procedure is utilized during the initial access or when the UE loses UL synchronization. The gNB can issue TA adjustment commands to the UE when its in a connected state. The steps in UL synchronization are as follows:

- The UE selects a preamble from a set of predefined preambles (for contention-based) or uses a preamble configured by the gNB (contention-free) and transmits it over the physical random access channel (PRACH).
- By detecting the preamble, the gNB can measure the coarse RTT. A quantized version of the RTT, known as TA, is then sent to the UE via the random access response (RAR).
- When the UE successfully receives the RAR, it adjusts its UL timing by the TA value.
- Although the initial TA is sent via the RAR, gNB can periodically send updated UL timing corrections to the UE via TA commands. These TA commands are crucial in maintaining UL synchronization in the event of UE mobility or clock drift.

The synchronization process is shown in Figures 1 and 2.

# B. Reference Signals

Several reference signals are used for channel estimation and positioning in 5G NR. Specifically, positioning reference signals (PRS) in the DL and sounding reference signals (SRS) in the UL are essential for many 5G NR positioning methods [4]. These reference signals were introduced in 4G and extended to 5G, offering better resolution and accuracy [19]. While the SRS is generated using the Zadoff-Chu sequence, PRS is generated using quadrature phase shift keying modulated 31-length gold sequence [19]. The OAI gNB and UE (nrUE) support both SRS and PRS. Detailed instructions for configuring the PRS in OAI can be found in [20].

# C. Zadoff-Chu sequences

Zadoff-Chu (ZC) sequences are widely used in 5G NR due to a number of desirable properties. A ZC sequence of length  $N_{\text{ZC}}$ , which must be an odd number, and root  $q \in [1, 2, ..., N_{\text{ZC}} - 1]$  is defined as

$$x_q[n] = \exp\left(-j\frac{\pi q n(n+1)}{N_{\rm ZC}}\right), 0 \le n \le N_{\rm ZC} - 1.$$
 (1)

Some key properties of the ZC sequences are given below.

- All the elements in a ZC sequence have unit amplitude.
- Normalized cyclic auto-correlation: When the root q is relatively prime to  $N_{\rm ZC}$ ,

$$\frac{1}{N_{\rm ZC}} \sum_{n=0}^{N_{\rm ZC}-1} x_q[n] x_q^*[(n+\nu) \text{mod}N_{\rm ZC}] = \delta[\nu], \quad (2)$$

where mod represent the modulo operation and  $\delta[\nu]$  represents the Kronecker delta function. There are  $N_{\rm ZC}$  unique cyclic shifts of the sequence  $x_q[n]$ .

• Normalized cyclic cross-correlation: when  $|q_1 - q_2|$  and  $N_{\rm ZC}$  are relatively prime,

$$\frac{1}{N_{\rm ZC}} \sum_{n=0}^{N_{\rm ZC}-1} x_{q_1}[n] x_{q_2}^*[(n+\nu) \text{mod}N_{\rm ZC}] = \frac{1}{\sqrt{N_{\rm ZC}}}.$$
 (3)

• The discrete Fourier transform (DFT) (or its inverse) of a ZC sequence is also a ZC sequence.

# III. PRIOR ART

The existing approaches for obtaining RTT in the cellular networks, termed as *Scheme A*, *Scheme B*, and *Scheme C* are presented in this section. While *Scheme A* and *Scheme B* are in 3GPP standards; *Scheme C* is a recently proposed enhancement.

*Scheme A*: RTT can be obtained at the gNB from PRACH during the RA procedure. This process is outlined in Section II-A and illustrated in Figure 1.

The RTT accuracy of this approach is limited by the low bandwidth of the RACH signal. Moreover, the RA procedure is performed only during the initial access or in the event of UL synchronization failure.

Scheme B: Using wideband reference signals like SRS and PRS, UE and gNB can estimate the receive-transmit timing



Figure 3. Estimation of RTT in Scheme B.

difference (Rx-Tx time difference) measurements. Figure 3 depicts this method. The RTT is calculated as

# RTT = UE Rx-Tx time difference

$$+$$

# gNB Rx-Tx time difference.

The ECID type I scheme [7], [8] and multi-RTT scheme in 5G NR [9], [10] follow this method. The details of Rx-Tx time difference measurement reporting is provided in [21].

Scheme B's RTT estimation is more accurate than Scheme A's, as we use wideband reference signals. However, this performance comes at the expense of increased latency and resource consumption, as the UE must send its Rx-Tx time difference measurements to the network.

**Scheme C:** Recently, the authors in [17] proposed a RTT estimation scheme by combining the TA measurement obtained from PRACH and SRS channel measurements. This method considerably improves the RTT estimation performance compared to *Scheme A* while not incurring extra UE Rx-Tx time difference measurement reporting costs as in *Scheme B*. Moreover, RTT can be obtained even when the 5G UE is in a radio resource control (RRC) inactive state. The signaling scheme is presented in Figure 4.

The drawback of *Scheme C* lies in the fact that a contentionfree RA procedure is required to estimate the RTT, resulting in additional radio resource consumption and increased latency.

In this work, a novel RTT method that overcomes the shortcomings of the above mentioned state-of-the-art schemes is presented.

## IV. DETAILED DESCRIPTION

The proposed method relies on PRS and URS to obtain the RTT. The central idea is to use the current TA and the delay (in samples) estimated from PRS at the UE as a cyclic shift while generating the URS. We present the generation and reception of the URS followed by the signaling procedure.



Figure 4. Signaling mechanism in Scheme C [17].



Figure 5. URS transmission at UE.

#### A. Uplink reference signal

The URS base sequence  $x_q[n]$  with root  $q \in [1, ..., N_{ZC}-1]$ is generated according to (1), whose properties are outlined in Section II-C. Let the cyclic shifted sequence is denoted by  $x_{q,\nu}[n] =: x_q[(n - \nu) \mod N_{ZC}]$ , where  $\nu$  is the cyclic shift. The following property plays an essential role in the proposed method,

$$x_{q}[n] \xrightarrow{\mathcal{F}} X_{q}[k]$$
$$x_{q,\nu}[n] \xrightarrow{\mathcal{F}} X_{q}[k] \exp\left(-j\frac{2\pi k\nu}{N_{\text{ZC}}}\right)$$

where  $\mathcal{F}$  denotes the Fast Fourier Transform (FFT) operation and  $0 \leq k \leq N_{\text{ZC}} - 1$ . Note that there are  $N_{\text{ZC}}$  unique cyclic shifts.

# B. Transmit and Receive Chain

The transmitter block in an orthogonal frequency-division multiplexing (OFDM) based system, as in 5G NR, is shown in Figure 5. The time-domain URS signal generated at the UE is denoted by  $x_{q,\nu}[n]$ .

The received time domain baseband signal at the gNB can be written as

$$y[n,\tau] = x_{q,\nu}[n] \circledast h[n-\tau] + w[n], 0 \le n \le N_{\text{ZC}} - 1$$

where h[.] denotes the wireless channel inducing a propagation delay  $\tau$ ,  $\circledast$  denotes the circular convolution and w[.] is the additive white Gaussian noise (AWGN). The receiver block at the gNB is shown in Figure 6. After performing FFT

$$Y[k,\tau] = X_{q,\nu}[k]H[k]e^{-j\frac{2\pi k\tau}{N_{\rm ZC}}} + W[k], 0 \le k \le N_{\rm ZC} - 1,$$



Figure 6. URS receiver at gNB.



Figure 7. Cyclic shifted URS CIR.

where H[k] and W[k] are the frequency domain channel and AWGN at k-th sub-carrier, respectively. By doing the correlation with the base reference signal sequence,

$$Y[k,\tau]X_{q}^{*}[k] = H[k]e^{-j\frac{2\pi k\tau}{N_{ZC}}}X_{q,\nu}[k]X_{q}^{*}[k] + \tilde{W}[k].$$
$$= H[k]e^{-j\frac{2\pi k(\tau+\nu)}{N_{ZC}}} + \tilde{W}[k].$$

After doing IFFT

$$\tilde{y}[n,\tau] = \mathcal{F}^{-1}\left\{Y[k,\tau]X_q^*[k]\right\} = h[n-(\tau+\nu)] + \tilde{w}[n]$$

The peak of the CIR  $|\tilde{y}[n, \tau]|$  at  $\tau + \nu$  corresponding to the cyclic shift  $\nu$  and propagation delay  $\tau$ .

# C. Cyclic shift based RTT

Leveraging the properties of the URS, we now present our cyclic shift based RTT estimation method. The signaling scheme is presented in Figure 8 and summarized as follows:

- The gNB configures the URS and PRS resources and prepares the UE by sending the downlink control information (DCI) through the physical downlink control channel (PDCCH) [17] or by RRC signaling [9].
- UE will measure the channel impulse response (CIR) first peak,  $p_d$  samples, derived from the PRS
- The cyclic shift of  $TA + p_d$  is applied on the base URS sequence  $x_q[n]$  resulting in  $x_q[(n TA p_d) \mod N_{ZC}]$ .
- UE transmits the URS
- The delay estimated from URS derived CIR first peak at the gNB will give

$$RTT = 2\tau - TA - p_d + \overbrace{TA + p_d}^{Cyclic shift}$$
$$= 2\tau.$$

This is illustrated in Figure 7.

Note that the cyclic shift must satisfy  $0 \leq TA + p_d < N_{ZC}$ .



Figure 8. Signaling for cyclic shift-based RTT Scheme.

In Table I, we compare the signaling overhead involved in RTT schemes. In the next section, we discuss the extensions to the proposed scheme to multiple users, and when the TA value is greater than the URS sequence length.

## V. EXTENSIONS

#### A. Larger Timing Advance

For large TA values, the proposed scheme can be extended by using multiple base URS sequences having different roots. For example, let us consider a scenario where  $0 \leq \text{TA} + p_d < 2N_{\text{ZC}}$ . Here the gNB can configure the UE with two URS base sequences  $x_{q_1}[n]$  and  $x_{q_2}[n]$ . The URS generation at UE is given by

- if  $0 \leq TA + p_d < N_{ZC}$ , generate  $x_{q_1}[n (TA + p_d) \mod N_{ZC}]$
- if  $N_{\text{ZC}} \leq \text{TA} + p_d < 2N_{\text{ZC}}$ , generate  $x_{q_2}[n (\text{TA} + p_d N_{\text{ZC}}) \mod N_{\text{ZC}}]$ ,

The roots are selected such that  $q_1$ ,  $q_2$  and  $|q_1 - q_2|$  are relative prime with  $N_{ZC}$ . The gNB can detect the delay and the root index using the auto and cross correlation properties stated in (2) and (3). If the URS peak, denoted by  $p_u$ , is detected at the gNB by doing correlation of the received signal with

- base sequence  $x_{q_1}[n]$ , then  $RTT = p_u$
- base sequence  $x_{q_2}[n]$ , then RTT =  $N_{ZC} + p_u$

## B. Multiple Users

Multiple UEs can be multiplexed in an OFDM symbol using the comb structure in the frequency domain similar to SRS [19]. This way, we can estimate the RTT from multiple UEs using the same OFDM symbol. The detailed implementation and performance analysis of these extensions are out of scope and are left for future work.

# VI. EXPERIMENTAL SETUP

To experimentally validate the proposed method, we consider a scenario where a single antenna gNB and a UE communicate over a line-of-sight channel. The gNB and the UE rely on the OAI 5G NR protocol stack [22] and USRP B210 software-defined boards. Moreover, the SC2430 NR signal conditioning module is used as an external RF front-end at the gNB [23]. The experiment is performed in an anechoic chamber at the Northeastern University Innovation Campus at Burlington, as shown in Figure 9. The gNB and UE operate in 5G NR band n78 with the system parameters listed in Table II. We use the phy-test mode of the OAI [24]. This mode allows us to run the OAI UE and gNB physical layer procedures while abstracting the higher layer protocol stack. The hardware delays are calibrated and later compensated in the channel measurements. We have enhanced the OAI software stack to implement the proposed scheme presented in Figure 8.

**URS support in OAI:** While the PRS is already implemented in OAI, we have added the URS feature in OAI nrUE and gNB. The URS implementation follows Figures 5 and 6. The URS base sequence is a ZC sequence of length  $N_{ZC}$ , with  $N_{ZC}$  being prime and  $N_{ZC} < K$ , where K denotes the FFT size. While mapping into the OFDM symbol, the remaining  $N_{ZC} - K$  resource elements (REs) are filled with zeros. Due to this up-sampling effect, the cyclic shift applied to the URS is calculated as

$$\nu = \left[ (\mathrm{TA} + p_d) \times K / N_{\mathrm{ZC}} \right],\tag{4}$$

where TA (in samples) is the current timing advance at the nrUE and  $p_d$  is the peak (in samples) detected from the PRS channel estimate.

The PRS is transmitted on 12 symbols of slot 1 of every frame by the gNB, and URS is transmitted in symbol 13 of slot 8 of each frame by the nrUE<sup>1</sup>. The UE applies the cyclic shit (based on the received PRS and TA) calulated in (4) on the URS sequence transmitted in slot 8. The TDD slot pattern is listed in Table II. With these modifications in the OAI stack, we can experiment with the proposed framework.

Table II
SYSTEM PARAMETERS

Parameters	Values
TDD slot configuration	DL DL DL DL DL DL DL Mixed UL UL
System bandwidth	38.16 MHz
Subcarrier Spacing $(\Delta f)$	30 KHz
Centre frequency $(f_c)$	3.69 GHz
Sampling rate $(f_s)$	46.08 MHz
FFT size $(K)$	1536
URS bandwidth	37.77 MHz
URS length $(N_{\rm ZC})$	1259
PRS bandwidth	37.44 MHz
PRS symbols	12
PRS Comb	2

<sup>1</sup>Note that this can be made flexible and left for future implementation.

## VII. RESULTS

The performance of the proposed RTT estimation scheme is evaluated in terms of empirical cumulative distribution function (CDF) of the range estimation error in low and high UL SNR scenarios. The CDF is obtained from 48,000 channel measurements collected using the signaling procedure illustrated in Figure 8 and the setup described in Section VI. These measurements are obtained by fixing the position of the gNB and moving the UE in a straight line between 3 to 10 meters with a 1-meter increment. At every point and SNR, a total of 6,000 measurements are collected. The experiment is performed in an anechoic chamber, as shown in Figure 9.

We apply two algorithms, namely, the peak detector (PD) and the matched filter (MF) on the collected URS channel estimates to obtain the empirical CDF. The range estimated using PD and MF is given by

$$\hat{l} (\text{PD}) = \frac{\mathbf{c}}{2f_s} \times \frac{1}{M} \sum_{m=1}^{M} \arg \max |\tilde{\boldsymbol{y}}_m|,$$
 (5)

$$\hat{d} (\mathrm{MF}) = \frac{c}{2} \times \arg\max_{\hat{\tau}} \boldsymbol{v}(\hat{\tau})^{\mathrm{H}} \mathbf{R}_{\mathbf{y}} \boldsymbol{v}(\hat{\tau}), \qquad (6)$$

where

$$\mathbf{R}_{\mathbf{y}} = \frac{1}{M} \sum_{m=1}^{M} \boldsymbol{Y}_m \boldsymbol{Y}_m^{\mathrm{H}},$$

$$\begin{split} \tilde{\boldsymbol{y}}_m &= \left[\tilde{y}_m[0,\tau], \tilde{y}_m[1,\tau], \dots, \tilde{y}_m[K-1,\tau]\right], m \in [1,M] \text{ is the } \\ m\text{-th estimated URS CIR, } \boldsymbol{Y}_m &= \left[Y[0,\tau],Y[1,\tau],\dots,Y[K-1,\tau]\right]^{\mathrm{T}} \text{ is the } m\text{-th estimated URS channel frequency response, } M \text{ is the number of measurements, } \boldsymbol{v}(\hat{\tau}) &= [1,e^{-j2\pi\Delta f\hat{\tau}},\dots,e^{-j2\pi(K-1)\Delta f\hat{\tau}}]^{\mathrm{T}}, f_s \text{ is the sampling rate } \\ \text{and } c \text{ is the speed of light.} \end{split}$$

The CDF of the range estimation error for MF and PD algorithms at high and low UL SNR is shown in Figures 10 and 11. In the case of high UL SNR, the USRP TX gain of the UE is set to 89.5 dB, resulting in an estimated UL SNR of 30 dB, while in the case of a low SNR, the UE TX gain is reduced by 50 dB. The gNB USRP TX gain is fixed throughout the experiments. While the MF and PD schemes have similar performance at high SNR, the MF algorithm has significantly better performance in low SNR scenario. In the low SNR scenario, for M=20 measurements, the range estimation error of MF is below 0.8 meters for 90% of the time. Furthermore, by increasing the number of measurements from M=20 to 60, we see an improvement in the performance for both methods.

#### VIII. CONCLUSION

This work has introduced a novel mechanism that facilitates the estimation of RTT between a UE and gNB. Our method comes with a reduction in overhead and latency compared to the existing schemes. The proposed method relies on PRS and a ZC sequence-based wideband URS. We have enhanced the OAI 5G protocol stack with the URS feature and validated the proposed scheme with real-time over-the-air experiments. Future work includes extending to multiple users and large timing advance values. Because of its simplicity and reduction



Figure 9. Experimental setup in the anechoic chamber.



Figure 10. CDF of the range estimation error.



Figure 11. CDF of the range estimation error.

in radio resource overhead, we believe it is a good candidate for positioning and sensing in 6G systems.

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