

Accuracy and Repeatability Results of a 5G Sub 6GHz Time of Arrival Distance Measurement Campaign for Industry 4.0 Localisation

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Abstract— Indoor localization has recently experienced a surge in interest, primarily because of its ability to offer a diverse range of services by utilising the Internet of Things (IoT) and widespread connectivity. This study presents a measurement campaign conducted to assess the precision and consistency of a 5G Sub 6GHz Time of Arrival system. The system is capable of measuring time intervals with a resolution of 0.3 picoseconds, which corresponds to a distance resolution of 0.1 mm. Due to the system's susceptibility to environmental noise and multipath reflections, fixed directional antenna array were implemented to enhance the received signal strength in the intended direction and reduce the impact of multipath reflections. The numerical test results demonstrate that distance can be measured with a precision ranging from 3.5 cm to 4.5 cm, ensuring consistent and reliable measurements. Precise localization has a significant architectural effect by enabling accurate beam-steering between ORAN (Open Radio Access Network) and UEs (User Equipment), resulting in the creation of more sustainable and energy-efficient networks.

Keywords— 5G Sub 6GHz Distance Measurement Campaign, Time of Arrival, distance accuracy, repeatability test, Industry 4.0.

I. INTRODUCTION

The proliferation of smartphones and other wireless devices in recent years has resulted in the emergence of diverse services, such as indoor localization. Indoor localization is the process of accurately determining the location of a device or user within an indoor setting or environment. Extensive research has been conducted on the localization of indoor devices in the past few decades, with a focus on industrial settings, wireless sensor networks, and robotics. Within the past ten years, the increasing use of smartphones and wearable devices equipped with wireless communication capabilities enabled the tracking and locating of these devices, consequently enabling the tracking and locating of the users themselves. This advancement also facilitated the emergence of a multitude of applications and services associated with this technology [10]. User and device localization have wide-ranging applications in sectors such as the health industry, manufacturing, disaster management, building management, surveillance, and others [11]–[13]. Moreover, it can offer benefits to a range of developing systems, including Internet of Things (IoT) [14], intelligent structures (such as smart cities [15], smart buildings [16], and smart grids [17]).

However, it is important to note that long-range IoT technologies do not currently have the capability to provide indoor localization. Nevertheless, many IoT applications will

require the ability to seamlessly and universally locate and navigate both stationary and mobile devices, both indoors and outdoors. Conventional short-range communication technologies can provide a fairly accurate estimation of the indoor position of an IoT device in relation to certain reference points. However, the exact global location of these devices, in terms of longitude-latitude geographic coordinates, cannot be determined unless the global location of the reference points is also known. Emerging long-range IoT technologies have the capability to approximate the worldwide location of a device by utilising the known locations of their access points. However, their accuracy is considered to be very poor, particularly in indoor settings [10].

The IoT aims to enhance the efficiency of various systems in areas such as healthcare, marketing, automation, monitoring, parking, transportation, retail, fleet management, security, disaster management, energy efficiency, and smart architecture [18]. By 2025, it is anticipated that the Internet of Things (IoT) will be integrated into various aspects of our daily lives, including food packaging, home appliances, furniture, and more [19]. This suggests that the IoT is a technology that will be prevalent in the future and has the capacity to be widely adopted. Integrating indoor localization into IoT will enhance the diverse range of services that IoT can offer [10].

The localization of user equipment (UE) in mobile communication networks has consistently been advocated since the initial stages of the 3rd Generation Partnership Project (3GPP) up to the 5th Generation (5G) with its intended use cases. Various industries, including future factories, healthcare, autonomous vehicles, energy, and urban environment automation, necessitate localization accuracy with a precision of up to 1 mm. This level of accuracy is crucial for enabling a wide range of new applications. Current 5G indoor localization systems endorsed by 3GPP can be classified into three categories: received signal strength (RSS), time-of-arrival (ToA), and angle-of-arrival (AoA) technologies, all operating within the sub-6 GHz/mmWave frequency range. The effectiveness of indoor localization using RSS is influenced by the physical arrangement, signal loss, and interference in the channel. On the other hand, the performance of AOA-based and TOA-based indoor localization can be significantly compromised by the NLOS propagation characteristic, which makes it challenging to

detect the direct signal path and accurately measure the signal propagation time, respectively [2].

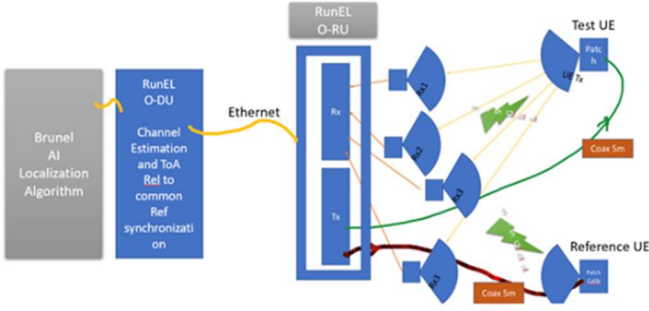


Figure 1: Setup for Ultra Accurate UE location measurement

The goal of this research is to measure the delay of a Sub 6GHz ToA Pseudorandom Noise (PN) Reference Signal whose duration, periodicity, spacing over frequency domain could be flexibly customized to meet applications requirements. A practical proposal of how Sub 6G mmWave ToA PN Reference Signals Measurement at Physical Layer in RAN can be performed to estimate distance using a smart loop back technique between the RAN downlink transmitter and uplink receiver to ensure reference signal compatibility and synchronisation, as shown in Figure 1.

The O-RU is configured in a Loop-Back Mode, which enables it to transmit 5G signals (Tx) at 3.5GHz similar to the UE transmissions. These Tx signals are connected via coax to two patch antennas that simulated the Test UE and the Reference UE. The Reference UE is a UE with a known location that is used to accurately calibrate the test UE location measurement. The test antenna is located on a scanner that can accurately move its position to new locations in space. The 5G signals transmitted over the air at 3.5GHz by the Test UE and the Reference UE patch antennas are received by the O-RU Receiver (Rx) via four different Rx antennas located in the four corners of the measurements room ceiling. The O-RU continuously measures the ToA of the 5G signals coming from the test UE and the Reference UE and transfer the results to the O-DU using ethernet packets with functional application platform interface (FAP) format for the data [3] that stores measurement results on an agreed memory sharing register.

An analysis of recent reported advancements in indoor localization with high precision using 5G signals, is presented. The objective of Li and Zhang's preliminary research is to achieve centimetre-level precision by integrating estimates of the arrival angle (AoA) and time of flight (ToF) of 5G signals. A diverse array of circumstances, including various configurations of antennas and signal-to-noise ratios, were employed in order to demonstrate resilient performance. Based on simulation results, it was possible to predict achievement of centimetre-level precision primarily in LOS scenarios [5].

Liu and Chen proposed a method for estimating the time-of-arrival (ToA) with high precision using downlink signals from 5G networks. They discuss the difficulty associated with delivering precise location-based services within enclosed spaces. Their primary aim is to use 5G signals in order to achieve precise indoor positioning. The authors incorporated machine learning algorithms into the estimation

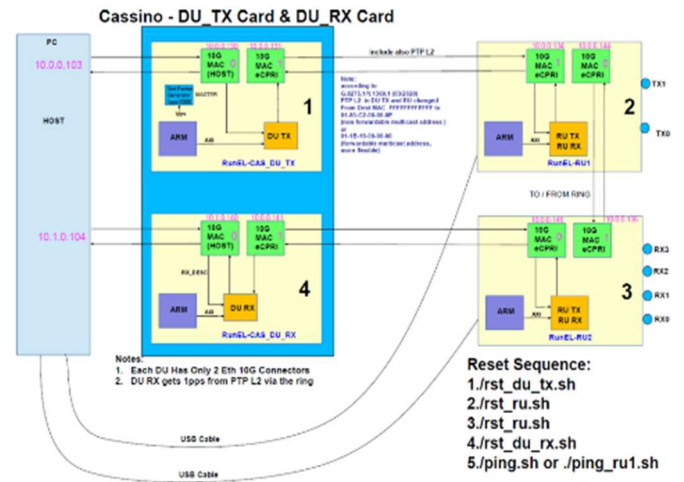
of ToA for 5G signals. The paper displayed the practical implementation of the proposed software-defined receiver (SDR), which enables indoor navigation utilising 5G signals and achieves a high degree of accuracy in pseudo-range measurements [6]. The statistical outcomes of the two methods in relation to the error in pseudo-range measurement, using the same test data. When using the 5G signal carrier phase ranging method, the pseudo-range measurement error has a cumulative distribution function (CDF) of 0.62 m at the 95% confidence level. On the other hand, when the 5G signal Support Vector Machine (SVM) method is used, the CDF of the pseudo-range measurement error is 0.50 m [6].

The paper by Sahmaei and Kassas extracts Time of Arrival (ToA) data while using the persistent SS/PBCH block in 5G signals via a custom SDR for opportunistic navigation, with a focus on extracting ToA data [7]. It presents a novel solution to the issue of unreliable autonomous ground vehicles (AGVs): opportunistic navigation utilising 5G signals. The method seeks to improve both precision and privacy, surmounting the constraints of conventional network-based positioning techniques. Experimental outcomes employing authentic 5G signals substantiate the effectiveness of the suggested remedy, proving enhanced dependability and precision in guiding AGVs. According to the findings, the estimated pseudo-range using an SS/PBCH signal had a standard deviation of 1.19 m [7].

Approaching the difficulties associated with reaching precise positioning in non-line-of-sight (N-LoS) environments, Muusrepp and Kulmar suggest techniques for the automated categorization of LoS/NLoS channels [8]. In addition to proposing alternative methodologies like angle-based measurements or Round-Trip Time (RTT). The paper's conclusions underscore the attainability of precise positioning under line-of-sight (LOS) conditions; nevertheless, difficulties manifest in non-LOS scenarios due to the substantial degradation of positioning accuracy caused by synchronisation errors [8].

II. AIM OF EXPERIMENT

The aim of the experiment is to measure the accuracy of Time of Arrival measurements between UE Tx Antenna and gNB Rx Antenna for a 5G Communication system in order to measure distance.



The requirement for the Host is for a PC using Linux Ubuntu OS 18.04 or 20.04 of which Brunel University is using. The PC has 2x RunEL DU Cards (Cassino cards) inserted in the PCI slots of the Host server, one using as DU_TX the second card as DU_RX. The PC has 2 x 10G Ethernet ports, one gets IP address 10.0.0.103, the second port gets IP address 10.1.0.104.

The RunEL Cards (Cassino cards) have 4 x 10G Ethernet, of which we are using only 2 x Ethernet ports per card. Ports connect with Small Form-factor Pluggable SFP+ Transceivers and Optic cables according to Figure 2.

The RunEL (Cassino Cards) Driver is setup and the Ethernet FIFO card drivers activated and the entire system booted up, as detailed for the Cassino Cards setup and the DU and RU are powered up in a specific sequence. For taking distance measurements the downlink, distance program and uplink shells are initiated in the specific order. The results are collected through RunEL's distance software, which displays the results of averaging of the measurement data.

III. TRACKING USERS IN TRAIN STATIONS

Mobile robots and Automated Guided Vehicles (AGVs) are the subject of a use case that has been identified by the 5G Alliance for Connected Industries and Automation (5G ACIA). Mobile systems like these are utilised on the manufacturing floor. A reference to this information can be found in [9]. Because they are able to handle tasks such as the driverless and autonomous transportation of materials and goods to and from production lines, automated guided vehicles (AGVs) are an essential component of the factory of the future. In addition, they have the capability to transport robotic equipment, such as a robot or gripper arm, to provide flexible assistance during the assembly procedure. This use case focuses on two essential aspects of automated guided vehicles (AGVs): Moving the video processing workload from an AGV camera to the edge computing node that is adjacent to it (as shown in Figure 1), with a significant demand for data rate (greater than 500 Mbps). Obtaining accurate localization of an automated guided vehicle (AGV) in a variety of scenarios, with a stringent requirement for localization accuracy (less than 1 centimetre).

These functions require the use of a wireless communication network to transfer data and determine location. This can be done in a data centre that is either nearby or distant. Figure 1 illustrates a specific instance of a Mobile AGV application in the industrial sector. This application utilises time of arrival (ToA) and angle of arrival (AoA) measurements from one or more 6G NodeB (NB) access points (AP) to determine the position of an automated guided vehicle (AGV). Furthermore, an advanced high definition (HD) camera is employed to monitor the environment surrounding the AGV, with the purpose of avoiding any potential collisions with objects in motion.

An Automated Guided Vehicle (AGV) fleet facilitates the transportation and movement of goods within a factory for logistical purposes. An Automated Guided Vehicle (AGV) can also function as a component of an assembly process by utilising a gripper arm equipped with sensors, which is mounted on the AGV, to pick up and position parts.

IV. INITIAL SYSTEM SETUP

The Time Difference of Arrival (TDoA) experimental setup is shown in Figure 3.

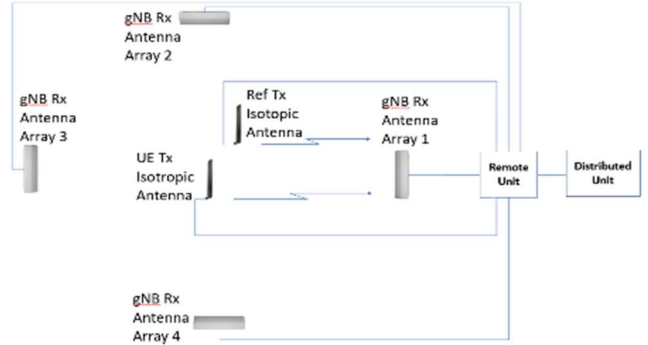


Figure 5: TDoA Experimental Setup for Location Measurement

The Remote unit has IP address 10.1.0.140. and the Distributed Unit (Dell 740 Server) 10.1.0.104. Initially Isotropic Antennas were intended for the Ref Tx Antenna and the UE Tx Antenna so that all four gNB Rx Antenna Arrays would be able to receive their transmitted OFDM signal, as shown in Figure 3, but the received signal was not sufficiently above the noise floor to enable detection and processing.

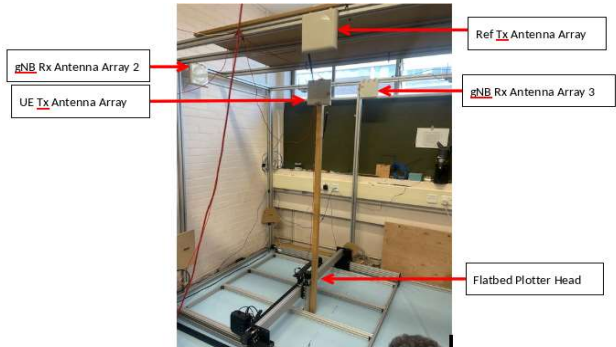


Figure 4: Experimental Set Up

Figure 4 shows the experimental setup from the view point of gNB Rx Antenna Array 1, which is directed towards Ref Tx Antenna Array and the UE Tx Antenna Array, which is fixed to the flat bed plotter that is able to move co-linearly closer or further from it under voice commands [4]. In the background can be seen gNB Rx Antenna Array 2 and gNB Rx Antenna Array 3. The Ref. Tx Antenna Array is located at a known distance from the gNB Rx Antenna Array 1.

Instead, a fixed directional antenna array was required for the Ref. Tx Antenna and UE Tx Antenna so that a sufficiently strong received signal above the noise floor could be obtained, the remote unit of which is shown in Figure 4, the circuit of which is shown in Figure 5.

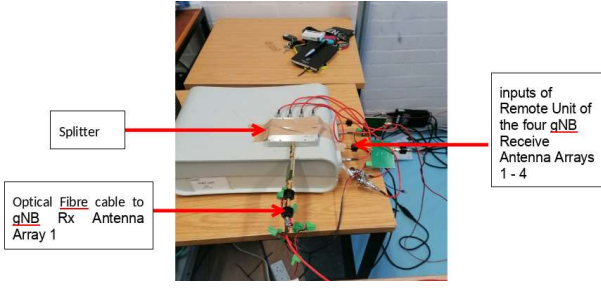


Figure 5: 5G Remote Unit and Splitter

Since the system was calibrated using coaxial cable end-to-end connections, compensation is required to be made for the segment of the end-to-end connection that was replaced by free space transmission.

The speed of light in vacuum is $c = 2.998 \times 10^8$ m/s, whereas the speed of an electrical signal in coaxial cable is about 2/3 of this, which is 1.998×10^8 m/s. The system is calibrated over coax with 0.66 c.

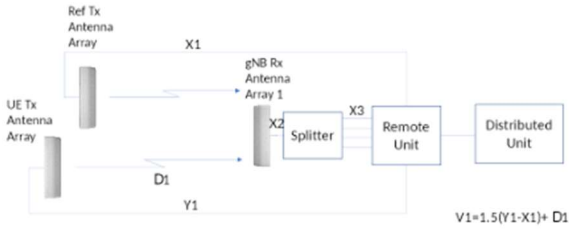


Figure 6: TDoA Experimental Setup with fixed directional UE antenna array for Location Measurement

$(Y_1 - X_1)$ is the difference in path lengths of the coax cables between the UE Tx Antenna Array and Ref. Tx Antenna Array, compensated by the ratios of speed of light in free space and the speed of light in coax cable = 1.5.

Δ_1 is the difference in path lengths in free space between the UE Tx Antenna Array and Ref Tx Antenna Array.

V_1 is the compensation required due to the different path lengths and propagation times in different media.

$$V_1 = 1.5(Y_1 - X_1) + \Delta_1$$

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Experiment 1: Recording from Same UE Tx and Ref Tx antennas

A fixed directional antenna array was required for the Ref Tx Antenna and UE Tx Antenna so that a sufficiently strong received signal above the noise floor could be obtained by the gNB Rx Antenna Array, which was split into four with a Splitter and fed into the intended inputs of Remote Unit of the four gNB Receive Antenna Arrays 1 - 4, as shown in Figure 8. Since the antenna array was not able to be beam-steered, then the UE Tx Antenna Array, Ref. Tx Antenna Array and gNB Rx Antenna Array were required to be co-linear with each other, as shown in Figure 7 in order to receive a sufficiently strong signal above the noise floor to enable processing of the OFDM signal for obtaining ToA.

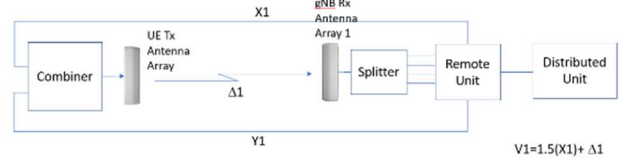


Figure 7: TDoA Experimental Setup for Location Measurement with single UE Tx Antenna Array

The capabilities of the system were placed through the following three tests in order to evaluate its performance repeatability. In order to make up for the lack of time during the integration meeting to collect additional data, measurements were taken at regular intervals of 20 centimetres. In addition, since the EM absorbers had not yet been delivered, so they could not be used during the integration meeting to absorb multipath reflections. Three tests were performed Test 1, 2 and 3 without absorbers (due to unavailability) for repeatability. One test was performed with absorbers after they arrived.

The measured data was recorded with the total distance travelled was 120 cm, whereas the measured distance amounted to 156 cm, with increments of 20 cm using the voice controlled flat-bed plotter. Based on the results obtained for test 1, it was determined that the mean error was 31.4, whilst the stdev = 51.3. This was due to an outlier measurement, as shown in Figure 8.

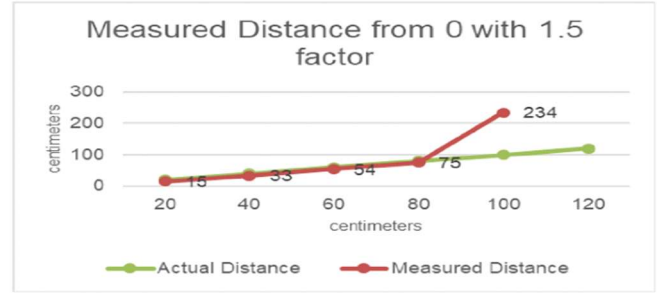


Figure 8: Test 1- Measured Distance from zero with 1.5 factor for single UE transmit antenna.

Test 2 results was obtained, it was determined that the mean error was 3.5, whilst the stdev = 2.1, as shown in Figure 9.

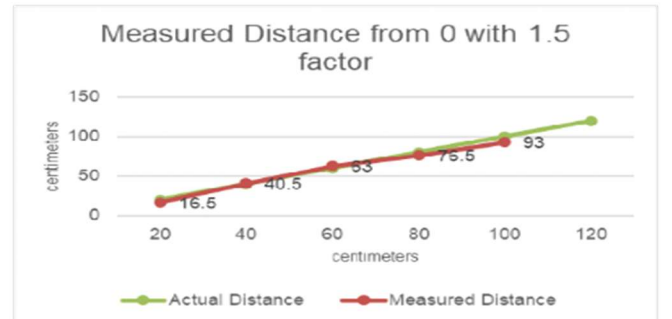


Figure 9: Test 2- Measured Distance from zero with 1.5 factor for single UE transmit antenna

Test 3 results was obtained, it was determined that the mean error was 3.2, whilst the stdev = 1.6, as shown in Figure 9.

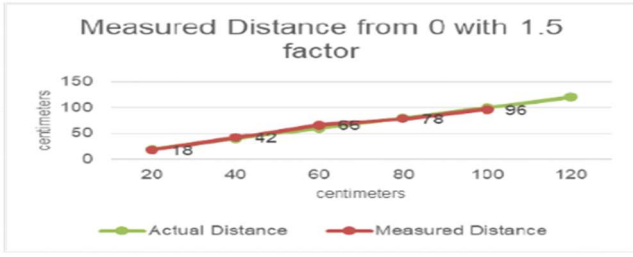


Figure 10: Test 3- Measured Distance from zero with 1.5 factor for single UE transmit antenna

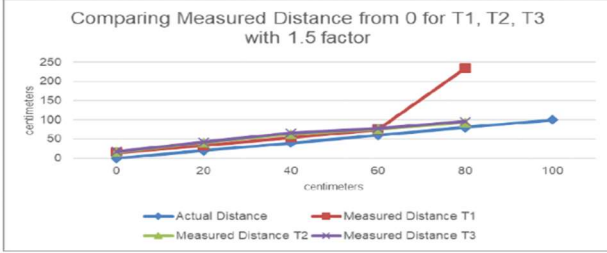


Figure 11: Test 1, 2, 3- Measured Distance from zero with 1.5 factor for single UE transmit antenna

Repeatability comparison between the three tests, the measured distance T_1 was very stable except for the one outlier in T_1 and similar to the other measured distances, as shown in Figure 11. However, it can be seen that T_1 increases drastically after 60cm. Overall, by comparing these tests it can be seen that the data follows a mutual trend, which allows us to assume that the data is reliable and reproducible.

B. Experiment 2 Recording from Separate UE Tx and Ref Tx antennas

System setup for experiment 2 is shown in Figure 12. Also EM Absorbers had been used throughout experiment 2

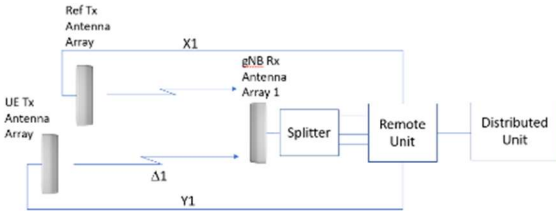


Figure 12: TDoA Experimental Setup for Location Measurement with single UE Tx Antenna Array and reference UE Tx Antenna Array

Test 1 results was obtained, it was determined that the mean error was 5.1, whilst the stdev = 4.0, as shown in Figure 13.

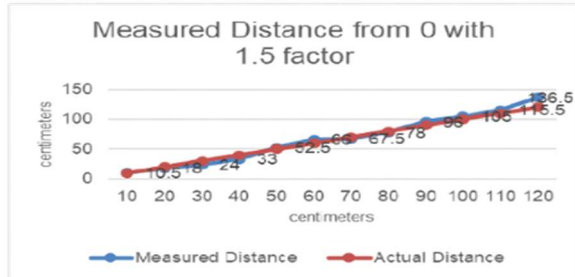


Figure 13: Test 1- Measured Distance from zero with 1.5 factor using Ref Tx and UE transmit antenna

Test 2 results was obtained, the mean error was 4.4, whilst the stdev = 4.0, as shown in Figure 14.

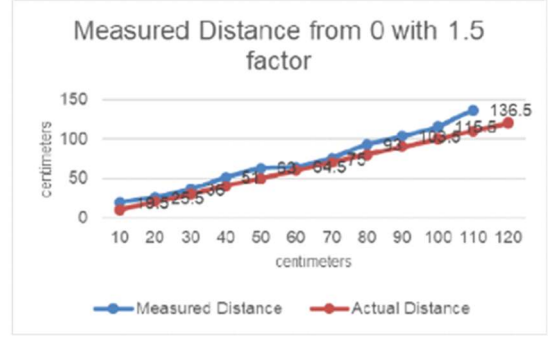


Figure 14: Test 2 with absorbers - Measured Distance from zero with 1.5 factor for single UE transmit antenna

VI. DETAILED MEASUREMENT DATA RESULTS AND ANALYSIS

A. Sniffing the Measurement Packets

Measurement data is transmitted by UDP packets using 5G functional application platform interface (FAPI) which is an initiative within the small cell industry released by Small Cell Forum (SCF) that establishes interoperability and innovation among suppliers of platform hardware, platform software and application software [3].

B. Analysing the data

95% of all samples on the Frequency of Occurrence Histogram shown in Figure 15 are $204340 \pm 172.45 \times 2 = 344.9$ time-ticks = 3.449 cm from the mean, which is approximately the same degree of accuracy obtained from the measurement campaign. On the time series Figure 16, spikes occur at slot 6, 43, 78, 115, 150, 187, 223 etc., i.e. between 35 to 37 slots apart. If it is due to interference from the flat-bed plotter stepper motor or the cooling fan motor then it is a problem because there will be plenty of these type of motors in factories, whereas if it is due to the FPGA system clock then it is also a problem. In both cases the design of EM shielding is required.

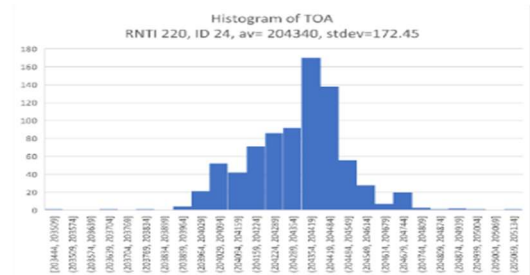


Figure 15 : Frequency Distribution of measurements for RNTI=220, *SECT=24

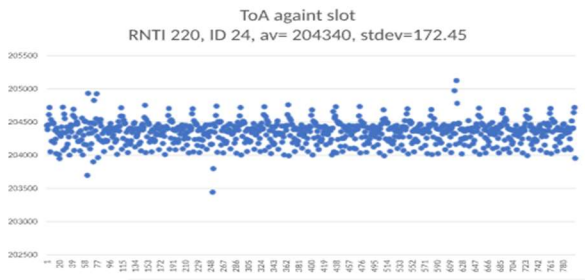


Figure 16: Time series of measurement data for RNTI=220, SECT=24

A summary of all the measurements mean, stdev and 95% CI are shown in Table 1. It indicates that the 95% CI at 68 cm for the four sections 24, 32, 40, 48 is around 3.5cm and for the four sections 64, 72, 80, 88 is around 4.5cm, which provides a good indicator of the accuracy of the system.

Table 1: Summary of Measurements of mean, stdev and 95% CI at 68 cm.

ID	mean (mm)	Stdev (mm)	95% CI (cm)
24	20434.0	17.245	3.449
32	20442.8	17.652	3.530
40	20329.1	17.578	3.516
48	20465.7	15.915	3.183
64	18297.9	21.806	4.361
72	18303.6	22.231	4.446
80	18199.5	22.503	4.500
88	18355.8	21.218	4.244

VII. CONCLUSION OF RESULTS

It has been shown from a measurement campaign on a 5G sub 6GHz Time of Arrival system, can measure distance with an accuracy of around 3.5 cm to 4.5 cm. The system measures the delay experience from a Pseudorandom Noise (PN) sequence transmitted from a User Equipment. Isotropic transmissions were initially used to transmit this PN sequence, but the delay measurement system was not able to compute reliable measurement of delayed time due to the effect of multipath. Beamformed transmissions from a fixed directional antenna array were subsequently used to transmit this PN sequence, which the delay measurement system was able to compute reliable measurement of delayed time due to the relative absence of multipath. Beamformed transmissions from a steerable antenna array would allow the system to measure distance to more than one access point (e.g. 4) from which location can be computed. Alternatively, location can be calculated from a single distance and an Angle from the steerable antenna array.

Measures are required to reduce the effects of multipath echoes including using less reflective mmWave or Infrared EM transmissions and signal processing if a system overcoming the multipath echoes can be developed.

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