

Experimental Characterization of Received 5G Signals Carrier-to-Noise Ratio in Indoor and Urban Environments

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Abstract—An extensive experimental study to characterize frequency range 1 (FR1) (i.e., sub-6 GHz) 5th generation (5G) signals from existing infrastructure for navigation is presented. The study uses a state-of-the-art 5G navigation software-defined radio (SDR) to track 5G signals in different environments and under different conditions to analyze the behavior of the received carrier-to-noise-ratio (C/N_0), which directly affects the precision of the navigation performance. Three different experimental scenarios were conducted for this purpose with real 5G signals and 4th generation (4G) long-term evolution (LTE) signals for comparison purposes: (i) a stationary indoor scenario to study the effect of wall and floor partitions, (ii) a stationary outdoor scenario to study the effect of sampling rate, antenna grade, and clock quality, and (iii) a mobile outdoor experiment to study the C/N_0 as a function of the range. All three scenarios confirmed the potential of downlink 4G and 5G signals for navigation.

Index Terms— 5G, 4G, LTE, carrier-to-noise ratio, navigation.

I. INTRODUCTION

The 5th generation (5G) cellular system (also known as new radio (NR)) has been showing a great potential in many applications beyond wireless communication, such as enabling new capabilities in future smart device connectivity, handling large data exchange for autonomous vehicles, and providing alternative positioning, navigation, and timing (PNT) solutions. This paper focuses on the latter application by characterizing the received power of sub-6GHz 5G signals.

The 5G system employs a similar structure to the 4th generation (4G) long-term evolution (LTE) system, as both systems use orthogonal frequency division multiplexing (OFDM) for downlink transmission. By design, the 5G system is very attractive for navigation purposes due to its following attributes: (1) high carrier frequencies (two main frequency ranges (FRs): (i) FR1, which spans frequencies from 450 MHz to 6 GHz and (ii) FR2, which spans frequencies from 24.25 to 52.6 GHz [1]), (2) abundance, (3) geometric diversity, (4) large bandwidth (up to 100 MHz and 400 MHz bandwidth for FR1 and FR2, respectively), and (5) high received power. This paper studies experimentally the received power of 5G signals. More specifically, the carrier to noise ratio (C/N_0) is characterized through extensive experiments. The C/N_0 is an important metric in determining the navigation performance with 5G signal: the higher the C/N_0 , the better the navigation precision.

The positioning capabilities of 5G have been studied in the recent years. Different approaches have been proposed, in which the direction-of-arrival (DOA), direction-of-departure (DOD), time-of-arrival (TOA), or a combination thereof is used to achieve accurate positioning with 5G signals. In [2], the authors investigated the positioning performance of six different 5G impulse radio waveforms, at the time when there were no generally accepted 5G waveforms yet. The analysis showed the capability of millimeter waves (mmWaves) in achieving sub-meter level accuracy, and the best performance was achieved with Gaussian raised-cosine, Gaussian pulse, and Sinc-RCP impulse radio waveforms. The capability of massive multiple-input-multiple-output (mMIMO) systems in providing accurate localization through DOA measurements was studied in [3]. The paper addressed the limitation of DOA estimation in mMIMO systems in the presence of multipath by proposing a compressed sensing navigation framework, which relies on the channel properties to distinguish line-of-sight (LOS) from multipath components. The proposed algorithm showed sub-meter positioning accuracy in simulation. Another approach to reduce 5G small cell interference and multipath effect in angular localization methods by combining near-field and far-field effects was proposed in [4]. Simulation results showed that the proposed approach improves the angular resolution by orders of magnitude. In [5], an integrated global navigation satellite system (GNSS)/5G framework was developed with a particle filter, in which device-to-device (D2D) range and angle measurements were assumed between mobile terminals (MTs). An experiment was performed with simulated GNSS data and emulated 5G D2D data, where the integrated system reduced the GNSS position root mean-squared error (RMSE) from around 5 m to about 3 m assuming 10 MTs. In [6], a network-based positioning framework using joint TOA and DOA measurements was proposed using cascaded extended Kalman filters (EKFs). The proposed framework considered the clock biases between the user equipment (UE) and the 5G base stations (also known as gNodeBs or gNBs), and among the gNBs themselves. The framework was evaluated by simulating a real 5G scenario using three-dimensional (3-D) ray tracing, where a sub-meter-level positioning accuracy was demonstrated.

All the aforementioned studies are limited to unrealistic

assumptions, simulations only, and/or laboratory emulated 5G signals without any experimental demonstrations. The lack of experiments in the 5G literature is due to: (i) 5G gNBs being rolled over only recently in a few major cities, (ii) hardware limitations in transmitting and receiving mmWave signals, or (iii) the proposed navigation approaches are network-based approaches and require the user to subscribe to the network. In the latter situation, the positioning performance will be limited as only gNBs from a single serving cellular provider are used. Alternatively, 5G signals could be exploited opportunistically [7]–[9], increasing the number of available gNBs without compromising the user’s privacy by requiring network subscription. This paper characterizes a critical metric for measuring opportunistic navigation performance with 5G signals, namely the received C/N_0 . The paper studies experimentally (i) the effect of different indoor structures and floors on the 5G received C/N_0 , (ii) the effect of receiver antenna grade, receiver’s clock quality, and sampling rate on the C/N_0 , and (iii) the effect of distance between the receiver and the gNB.

The remainder of the paper is organized as follows. Section II discusses the methodology for calculating the C/N_0 of received 5G signals. Section III presents experimental results for both 5G and 4G signals in three different scenarios: (i) a stationary indoor scenario to study the effect of wall and floor partitions, (ii) a stationary outdoor scenario to study the effect of sampling rate, antenna grade, and clock quality, and (iii) a mobile outdoor experiment to study the effect of range. Concluding remarks are given in Section IV.

II. METHODOLOGY

This paper characterizes 5G signals from FR1, where most cellular providers use frequency division duplexing (FDD) due to its superior performance in providing better coverage and lower latency. The C/N_0 is obtained by tracking the primary synchronization signal (PSS) and the secondary synchronization signal (SSS) using the software-defined radio (SDR) proposed in [10]–[12]. The C/N_0 is calculated as

$$C/N_0 = 10 \log_{10} \left[\frac{\Delta f (C - \sigma_n^2)}{\sigma_n^2} \right],$$

$$C = \max_t \{ |\mathbf{h}(t)| \},$$

$$\sigma_n^2 = \frac{1}{\lceil \frac{3}{4}M \rceil - \lfloor \frac{1}{4}M \rfloor} \sum_{t_i = \lfloor \frac{1}{4}M \rfloor}^{\lceil \frac{3}{4}M \rceil} |\mathbf{h}(t_i)|^2,$$

where Δf is the subcarrier frequency, C is the carrier power, σ_n^2 is the noise power, $\mathbf{h}(t)$ is the impulse response estimated in the tracking loop of the navigation SDR, M is the length of $\mathbf{h}(t)$, and $\lceil \cdot \rceil$ denotes integer rounding towards $+\infty$.

III. EXPERIMENTAL RESULTS

This section characterizes the signal power of existing sub-6Ghz 5G signals currently in service and assesses their use for opportunistic navigation in different environments and setups. Three scenarios are presented comparing the C/N_0 of 5G and 4G signals: (1) a stationary, indoor scenario to study the effect

of wall and floor partitions, (2) a stationary, outdoor scenario to study the effect of the sampling rate, antenna grade, and receiver clock quality, and (3) a mobile, outdoor experiment to study the C/N_0 as a function of range.

A. Scenario 1: Stationary Indoors

This scenario studies the C/N_0 of 4G and 5G signals in indoor environments.

1) *Experimental Setup*: In the first scenario, the C/N_0 of FR1-5G and 4G signals are characterized indoors, where the effect of wall and floor partitions are studied. To this end, 5G and 4G signals were collected over durations of five minutes at 14 different locations in the Engineering Gateway building at the University of California, Irvine (UCI), USA. Out of the 14 locations, 12 are labeled with a number and a letter according to “ ij ”, where $i \in \{1, 2, 3, 4\}$ corresponds to the floor number and $j \in \{a, b, c, d, e, f\}$ corresponds to a building area. The remaining two locations are labeled “bridge” (an indoor bridge with glass walls on the 3-rd floor connecting the two buildings) and “elevator” (an elevator in the middle of the building which was going up and down between floors 1 and 4 during data collection). At each location, signals from two U.S. cellular providers were received: T-Mobile and AT&T, transmitting at four different frequencies in total, as summarized in Table I. Both gNB1 and eNodeB1 were located on top of the Engineering Tower building on the UCI campus. In addition to being from the same operator, gNB2 and eNodeB2 have the same cell ID. As a result, they are most likely co-located; however, their exact locations is not known. The receiver was equipped with four omnidirectional, low-grade, magnetic mount antennas connected to a quad-channel National Instruments (NI) universal software radio peripheral (USRP)-2955R to simultaneously down-mix and synchronously sample signals at the four carrier frequencies with a sampling rate of 10 mega sampled per second (Msps). The signals were processed in a post-processing fashion using the 4G and 5G modules of the Multichannel Adaptive TRAnsciever Information eXtractor (MATRIX) SDR implemented in MATLAB [10], [13]. Fig. 1 shows the environment layout in which the experiment was performed, the eNodeBs’ and gNBs’ positions from which signals were collected, and the experimental hardware and software setup.

TABLE I
E NODEB’S AND GNB’S CHARACTERISTICS

Base station	Carrier frequency [MHz]	N_{ID}^{Cell}	Cellular provider
gNB 1	872	872	AT&T
gNB 2	632.55	394	T-Mobile
eNodeB 1	739	93	AT&T
eNodeB 2	731.5	394	T-Mobile
eNodeB 3	751/2125	221	T-Mobile

2) *Experimental Results*: The C/N_0 values of the eNodeBs and gNBs in Table I at each location are shown in Fig. 2. The following can be concluded from these plots:

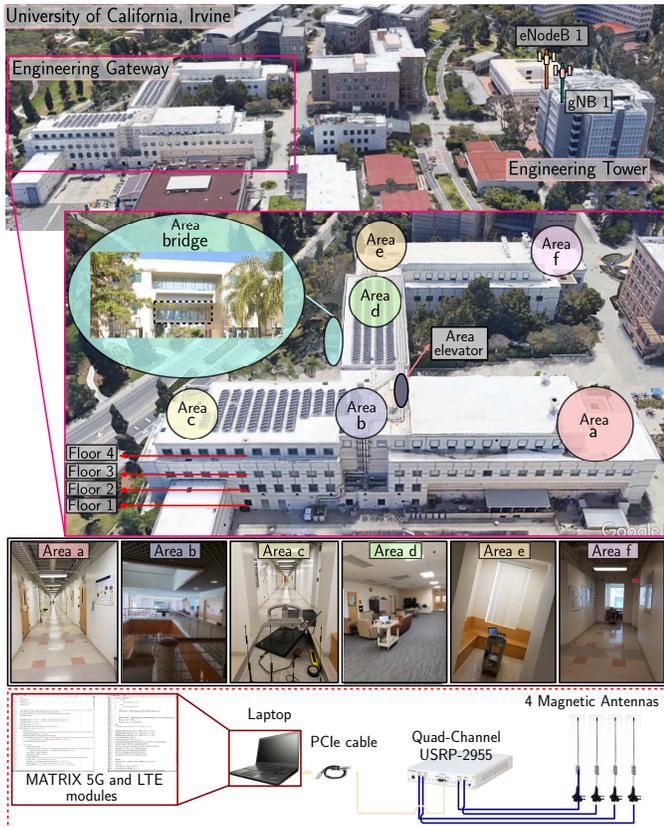


Fig. 1. Environment layout and hardware and software setup of scenario 1. Map data: Google Earth.

- Both 4G and 5G signals from both providers have consistently similar C/N_0 values at the different locations. As a result, similar navigation accuracy is expected with FR1-5G signals as with 4G signals.
- There does not seem to be a clear pattern in the C/N_0 behavior on different floors or areas in the building. This conclusion is surprising and implies that a consistent navigation performance is expected throughout the entire building.
- Although the elevator walls are metal, the signals inside the elevator are surprisingly powerful. This can be particularly useful as pedestrian-mounted receivers going up or down the floors can maintain track of 4G and 5G signals and do not need to re-acquire.

B. Scenario 2: Stationary Outdoors

In this scenario, the effect of sampling rate, antenna grade, and receiver clock quality on the C/N_0 is studied.

1) *Experimental Setup*: The receiver was placed on the roof of the Anteater parking structure on UCI campus, 300 m away from gNB1 and eNodeB1 with direct LOS. The hardware setup is similar to that of the stationary indoors setup in scenario 1, except that two of the omnidirectional low-grade antennas were replaced by two high-grade 10 Watts, omnidirectional Laird antennas with a gain of 1.5 dBi. The antennas were connected to the same USRP mentioned in the

previous setup to simultaneously down-mix and synchronously sample signals at the four carrier frequencies, which are then post-processed by the MATRIX SDR. The USRP's oscillator was operated in two modes: (i) as a GPS-disciplined oscillator (GPSDO) (precise frequency standard) and (ii) free running internal oscillator (typical oven-controlled oscillator (OCXO)). Moreover, the signals were sampled at (i) 10 Msps and (ii) 20 Msps to study the effect of the sampling rate on the C/N_0 . Fig. 3 shows the experimental hardware and software setup.

2) *Experimental Results*: The C/N_0 values of the 4G and 5G signals for different antenna grades, clock qualities, and sampling rates are shown in Fig. 4. The following can be concluded from these plots:

- As expected, the C/N_0 values with the high-grade (HG) antenna are consistently 3–6 dB higher than that with the low-grade (LG) antenna. While these results imply that investing in a high-grade antenna (around \$40 USD price difference) yields a 3–6dB gain in the C/N_0 , which goes a long way in low signal-to-noise ratio (SNR) applications, it is also important to notice that the C/N_0 values with the low-grade antenna are mainly above 50 dB-Hz. Such C/N_0 is high enough to produce a reliable navigation solution. Similar values were obtained indoors with the low-grade antenna, as indicated in Fig. 2.
- When operating with the GPSDO, the receiver produces stable values of C/N_0 . When operating with the USRP's internal OCXO, the C/N_0 values are less stable initially, but appear to stabilize around high enough C/N_0 values as time progresses. This implies that such signals are useful in GNSS-challenged environments (e.g., scenario 1 and in deep urban canyons) or in environments under spoofing or jamming attacks.
- There does not seem to be any noticeable gain in increasing the sampling rate from 10 Msps to 20 Msps, as the bandwidth of the 4G and 5G signals under study was 10 MHz.

C. Scenario 3: Mobile Outdoors

This scenario characterizes the C/N_0 as a function of the range r between the receiver and the gNB.

1) *Experimental Setup*: In this third scenario, the experiment was conducted on Fairview Road in Costa Mesa, California, USA. One of the high-grade Laird antennas was connected to the USRP, which was in turn mounted on a vehicle and tuned to listen to FR1-5G signals at a 872 MHz carrier frequency, which corresponds to the U.S. cellular provider AT&T. The gNB cell ID was 608 and its location was surveyed prior to the experiment. The USRP's GPSDO was used throughout this experiment. The vehicle was equipped with a Septentrio AsteRx-i V integrated GNSS-inertial measurement unit (IMU) whose x -axis pointed toward the front of the vehicle, y -axis pointed to the right side of the vehicle, and z -axis pointed upward. AsteRx-i V is equipped with a dual-antenna multi-frequency GNSS receiver and a VectorNav VN-100 micro-electromechanical system (MEMS) IMU. The loosely-coupled GNSS-IMU with satellite-based augmentation system (SBAS)

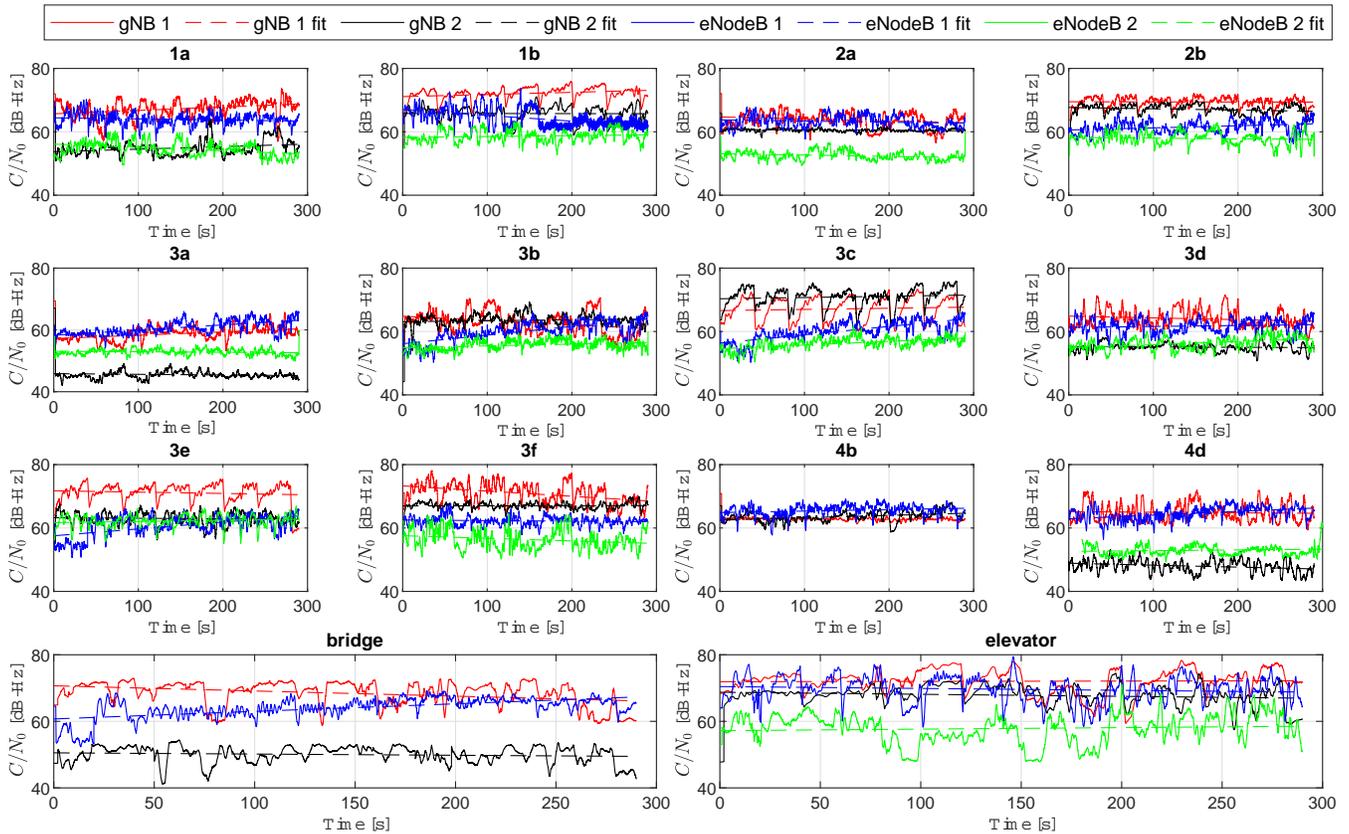


Fig. 2. Experimental results of scenario 1 showing the C/N_0 values of the 2 gNBs and eNodeBs 1 & 2 from Table I in different locations in the Engineering Gateway building on UCI campus. The solid and dash lines represents the estimated C/N_0 time history and the corresponding linear fit, respectively.

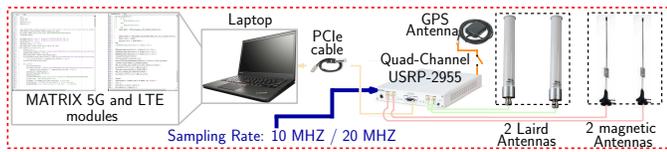


Fig. 3. Hardware and software setup of scenario 2. Map data: Google Earth.

navigation solution produced by AsteRx-i V was used as ground truth in this experiment. Fig. 5 shows the environment layout and the experimental hardware and software setup.

2) *Experimental Results:* The C/N_0 was computed along the trajectory and plotted as a function of the range between the gNB and the receiver and is shown in Fig. 6 along with a linear fit. The following can be concluded from this plot. While simple, the linear model seems to fit well the behavior of the C/N_0 in this semi-urban environment. Such models can be particularly useful for navigation framework design and analyses. Moreover, the received 5G signals are surprising powerful at more than 55 dB-Hz beyond 2 km, which is a typical cell size in semi-urban environments. This results implies that the receiver could reliably track signals from numerous 5G gNBs, which directly improves the navigation performance.

IV. CONCLUSION

The received power of 5G signals is assessed experimentally for opportunistic navigation using real 5G signals from existing infrastructure and a state-of-the-art 5G navigation SDR. The C/N_0 ratio of 5G signals was studied in three different scenarios: (i) a stationary indoor experiment, (ii) a stationary outdoor experiment, and (iii) a mobile outdoor experiment on a ground vehicle. The stationary indoor experiment assessed the C/N_0 of 4G and 5G signals for different floors and room structures, showing consistent behavior across locations. As a result, similar navigation accuracy is expected with FR1 5G signals as with 4G signals. The stationary outdoor experiment studied the effect of sampling rate, antenna grade, and clock quality on the received C/N_0 , showing that acceptable performance could be obtained with low-grade antennas and free-running OCXOs. The mobile experiment demonstrated that the C/N_0 could be modeled as a linear function of the range, and shows that the C/N_0 remains powerful beyond 2 km, which in turn implies that numerous gNBs can be used for navigation.

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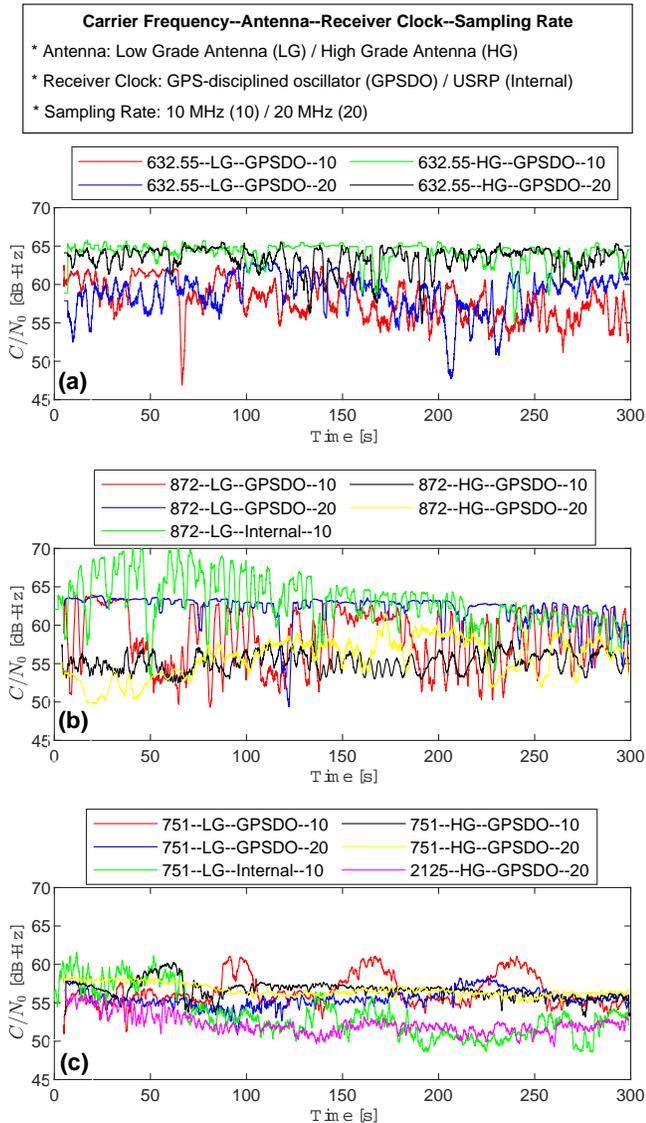


Fig. 4. Experimental results of scenario 2 showing the C/N_0 values of gNBs 1 & 2 and eNodeB3 from Table I for a stationary outdoor receiver and for different antenna grade, receiver clock quality, and sampling rate.

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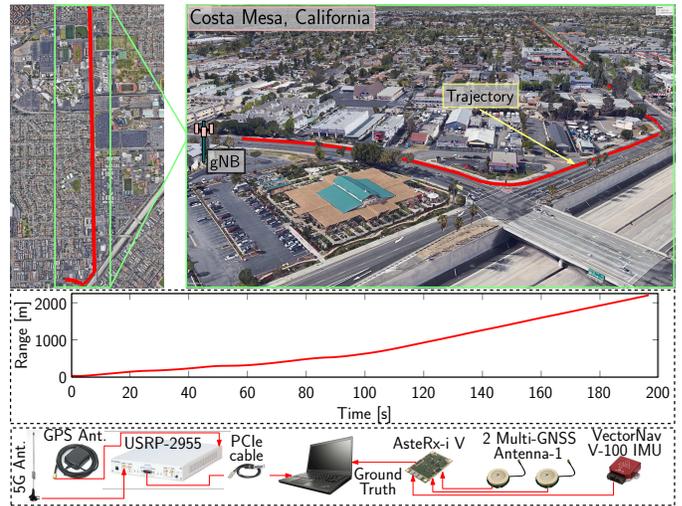


Fig. 5. Scenario 3: environment layout, hardware and software setup, and the range between the ground vehicle-mounted receiver and the gNB over the entire experiment. Map data: Google Earth.

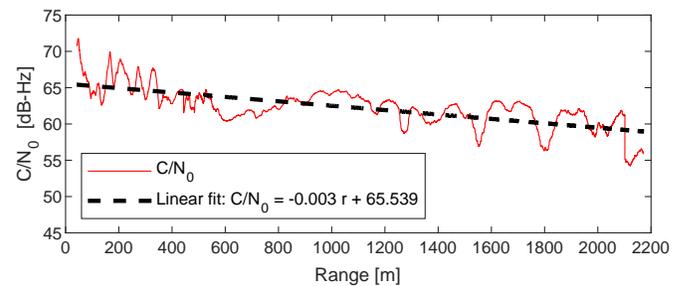


Fig. 6. Experimental results of scenario 3 showing the C/N_0 values of a gNB in a semi-urban environment as a function of the range between the gNB and an outdoor mobile receiver mounted on a vehicle.

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