User Localization in 5G Mobile Networks

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***Abstract*—5G technology enables accurate user location within centimeter range, which has led to the development of a multitude of new use cases. At first, this paper presents several use cases, like emergency response, transport and indoor navigation. Then the fundamental localization techniques proximity, trilateration and fingerprinting are presented. After that, three different categories of localization architectures are explained. Furthermore, user localization in 4G and 5G cellular networks is explored. 5G user localization benefits from increased bandwidth, smaller cells, device-to-device communication and multipath-assisted algorithms. Finally, open research topics like machine learning, heterogeneous networking protocols and beamforming schemes are discussed.**

***Index Terms*—User Localization, 5G, Context-Awareness, Tracking, Navigation, Positioning, Localization Architecture**

1. Introduction

The increasing ubiquity of the 5G network stirrs expectations towards user location estimation. Positioning with 5G has many benefits such as high coverage, high accuracy, low latency, low energy requirements and scalability. Historically, the main reason for the standardization of localization services in cellular networks were emergency calls (see 2.1). The standardization group 3rd Generation Partnership Project (3GPP) was formed as a worldwide organisation that develops protocols for mobile telephony [1]. Release 9 of the 3GPP was the first release to contain positioning protocols requiring network operators get the accurate position of emergency callers [2]. It was released in 2009. Further releases have improved the user localization. Release 17, which is scheduled for delivery in 2021, will include 5G Core Location Services [3]. 5G will improve accuracy through enhancements like high density of base stations, high signal bandwidths, device-to-device communication and millimeter wavelength technology [4] (see 6).

2. Use Cases

Different categorizations of use cases are possible: Bartoletti et al. [2] mention four different categories of use cases: regulatory and mission critical, location-based services, industry and eHealth, and transport. Laoudias et al. [5] choose the use case categories consumer, networking, industrial, health care, public safety and emergency response. Three use cases - emergency response, transport and indoor navigation - will be explored further in this paper.

2.1. Emergency Response

Nowadays, the majority of wireless 911 emergency calls are made indoors. Consequently, in 2015, the U.S.A. Federal Communications Commission (FCC) introduced new requirements for network operators to improve location determination for indoor as well as outdoor calls. The operators need to implement the following location rules: within 6 years, they must provide 50 meter horizontal accuracy for 80% of all wireless 911 calls and implement several requirements for provision of vertical location information [6]. For emergency responders, it is better to know the exact vertical position (the correct floor) and get the horizontal position slightly wrong than to have an inaccurate vertical position (the wrong floor) and have the exact horizontal position [5]. Emergency response service also includes sending an alert to nearby emergency responders via their phones and the localization service of emergency equipment outside hospitals [2].

2.2. Transport

The tracking of assets and freights leads to higher transportation efficiency. The localization of vehicles is needed for traffic monitoring, management, and control. For example, when the vehicle position is known, drivers can be taxed through road-user charging [2]. Although Global Navigation Satellite Systems (GNSS) are often used in vehicles, they have difficulties in non line of sight environments like urban areas or areas with dense foliage. Therefore, they are complemented with other positioning systems, for example radars, cameras and sensors [4]. For automotive use cases, the automotive industry expects location accuracy within a 10cm range for self- or assisted-driving applications. Automotive use cases include automated driving, road safety and traffic efficiency services, digitalization of transport and logistics, intelligent navigation, information society on the road and nomadic nodes [7]. For an unmanned aerial vehicle, accurate positioning is critical [2]. In the future, a combination of unmanned aerial and ground vehicles will be deployed in automated security and surveillance systems. They will be also used in military applications, remote monitoring and data acquisition applications and applications in photography, inspection and surveillance missions [8].

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2.3. Invented Use Case: Indoor Navigation Systems

Outdoor navigation systems are frequently used today. However, studies have shown that the average American spends 86.9% of his time indoors [9]. With improvements in vertical localization, indoor navigation systems, that guide people to their indoor destination, can be developed. This development will be especially useful for visually impaired people. Examples of buildings that might deploy indoor navigation systems are airports, office buildings, hospitals, hotels, universities and other government buildings, shopping malls and museums.

3. Fundamental Network Localization Techniques

The prevailing technology for outdoor localization, tracking, and navigation is the satellite system GNSS. Under ideal conditions GNSS delivers high accuracy (within a few meters). The disadvantages of GNSS receivers are high energy requirements, high time-to-first-fix and accuracy degradation in urban and indoor environments. The time it takes for the GNSS receiver to estimate the user location after it is turned on is called time-to-first-fix [5]. Because not all devices feature GNSS chips, other user localization methods that rely on wireless communication networks are also worth considering.

A rough estimation of the user location in wireless communication networks can be done with a technique called proximity. The location is estimated as the known location of the transmitter associated with the end device. Cell ID is a representative method for proximity. It estimates the user location as the location of the closest base station. Its accuracy depends on the density of transmitters [5]. Cell ID is the backup option when other methods can not be applied [1].

Trilateration is a method of determining the relative positions of three or more points by treating these points as vertices of a triangle or triangles of which the angles and sides can be measured [10]. Challenges of the trilateration approach are coverage, inter-cell interference, multipath channel and synchronization [1]. Possible measurements for trilateration are Time of Arrival, Time Difference of Arrival (TDoA), Direction of Arrival, Angle of Arrival and Received Signal Strength [2]. In order to improve system availability or localization accuracy, custom hybrid solutions can be implemented [5]. A combination of trilateration with GNSS is the most common hybrid solution [1].

Another popular technique is called fingerprinting or Radio Frequency Pattern Matching [1]. It addresses the problem of inaccuracy due to signal reflection and diffraction in urban areas. A database called radiomap is created, in which fingerprints (location-tagged signatures) are stored together with the corresponding location. The user can be located by finding the best match for a certain signal measurement, such as Received Signal Strength or time delay, with the fingerprints of the radiomap through pattern recognition [2].

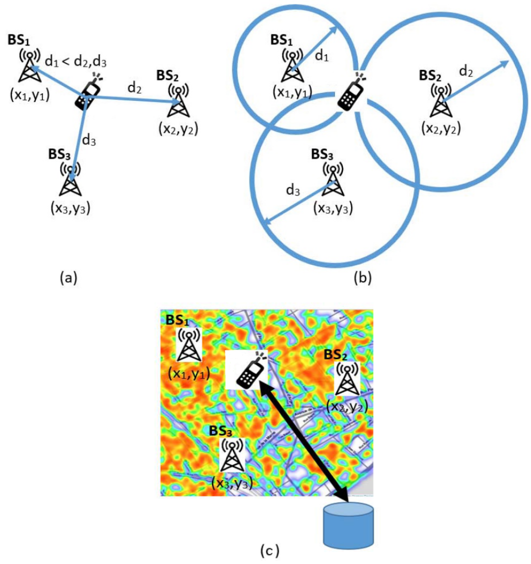

Figure 1. Illustrations of (a) proximity, (b) trilateration and (c) fingerprinting [5]

4. Localization Architectures

This subsection presents the three most common architectures, categorized by who estimates the location. Different aspects of a localization architecture, such as security, privacy and availability need to be considered. Nowadays, GNSS is regarded as critical infrastructure due to its use in essential systems like banking. In the future, indoor positioning will likely become part of the critical infrastructure as well. Therefore, service level availability is a concern. For example, emergency callers urgently need availability of the service and its location estimate. The service availability can be improved by redundancy, the location estimate by appropriate crowd-learning techniques [5]. Privacy is important for the user as well as the network operator: on the one hand, the user has the right that his location data is treated with confidentiality. The operator, on the other hand, has the right to keep the information about his network structure private [1].

In UE-based architectures, the user equipment (UE) estimates the location with assistance data from the the network. This approach is suitable for large user bases and situations in which location-awareness of the device is needed. Its advantages are low-cost and low-latency delivery. This approach is also more secure, because the network only provides assistance data. It can be implemented with radiomaps. Per building, a radio map can be obtained from a Content Delivery Network. With the radiomap, the UE is able to estimate its position within the building [5].

UE-assisted architectures are useful when the UE does not need to know the location information. An example is object tracking, where the location of the object only matters to the controllers. The UE measures certain signals, such as Wifi or Bluetooth signal strength and sends this data to the network. The UE does not need to be sophisticated, because it does not need to perform any calculations or store radiomaps. The network then does the location estimation. For each location event, a transaction

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is needed, which leads to a higher cost compared to the UE-based approach [5].

In network-based architectures, the network does the location estimation. This can be done, for example, by installing Bluetooth sniffers in a building. The disadvantages are the power and network connectivity requirements of the sniffers and the limited number of trackable devices. However, the advantage of this approach is its passiveness, meaning the UE does not need to do any measurements or calculations [5].

5. User Localization in 4G Cellular Networks

Release 9 supports three different localization methods: assisted GNSS, observed TDoA, and enhanced Cell ID. GNSS needs at least four satellites with clear line of sight to get a 3D position. Assisted GNSS tries to overcome that problem by having the network provide assistance data to the GNSS receiver [11]. With observed TDoA, the UE measures the time interval between the reception of downlink signals of two different neighbor base stations. The observed TDoA between base station 1 and base station 2 is the difference t2-t1, where t1 is the time of receiving the signal from base station 1 (t2 respectively) [11]. In order to calculate the position, the observed TDoA from at least three different pairs of base stations are needed [11]. Enhanced Cell ID uses the geographical coordinates of the closest serving base station and one of three additional measurements: the distance from one base station, the distance from three base stations or the Angle of Arrival from at least two base stations. The first two approaches are UE-assisted, the third one is network-based [11]. Observed TDoA is UE-assisted, whereas uplink TDoA is network-based [5].

Uplink TDoA, a method which calculates the position of the user by evaluating the time difference of LTE uplink signals sent to the base stations by the UE, was added in Release 11 [5]. Release 12 introduced Radio Frequency Pattern Matching. Release 13 added an observed TDoA enhancement, terrestrial beacon systems, WLAN, Bluetooth and barometric pressure sensor positioning. A terrestrial beacon system consists of ground-based transmitters, which complement GNSS by sending positioning signals. In barometric pressure sensor positioning, a barometer measures the air pressure. This approach has a vertical positioning accuracy below one meter. [1].

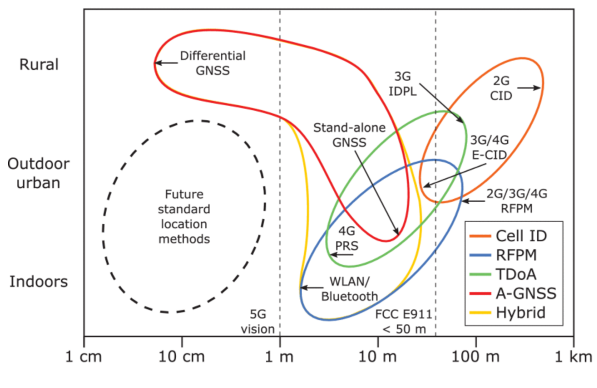

Figure 2. Expected horizontal accuracy of cellular mobile radio localization methods for indoor, outdoor urban and rural scenarios [1]

6. User Localization in 5G Cellular Networks

Release 15 supports assisted GNSS, WLAN, Bluetooth and barometric pressure sensor positioning techniques and TDoA on an LTE carrier. Release 16 reintroduces some positioning methods from LTE - such as observed TDoA, uplink TDoA, enhanced Cell ID - and introduces new methods such as Multicell Round Trip Time, uplink Angle of Arrival and downlink Angle of Departure. Whether Release 17 will introduce new positioning methods depends on analysis of the accuracy of Release 16 [12].

Localization possibilities will increase because of the introduction of new 5G features like mmWave technology. mmWave frequency is defined as 24-52.6 GHz [12]. mmWave technology has the twofold advantage of increased frequency and bandwidth. Furthermore, mmWave technology leads to a better resolution of multipath components. One challenge of mmWave technology is increased path loss, because the path loss is in proportion to the square of the carrier frequency. Other challenges are difficulties in diffracting around obstacles and penetrating through solid materials. For example, a brick wall causes 178 dB attenuation at 40 GHz [13].

Multipath-assisted localization techniques offer centimeter range accuracy [1]. Algorithms, for example Channel-SLAM, exploit multipath propagation to estimate the position of the UE. SLAM means Simultaneous Localization and Mapping. Channel-SLAM treats multipath components as signals emitted from virtual transmitters and can accurately estimate the location of the UE even if only one physical transmitter is available. Another advantage of Channel-SLAM is that it needs no prior information like for example a fingerprint database. It only needs to know the physical transmitter position, the initial receiver position and the moving direction [14].

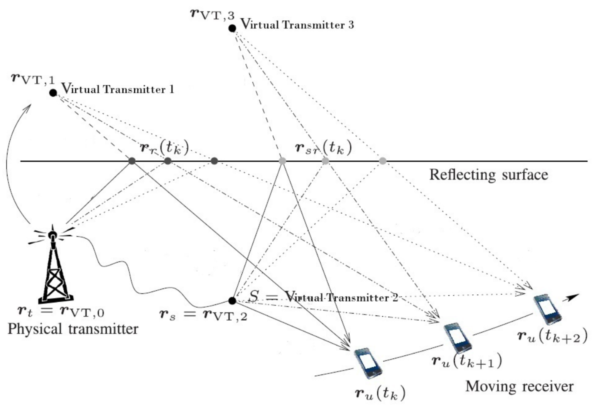

Figure 3. Illustration of Channel-SLAM [14]

Channel-SLAM takes into account reflection on a smooth surface and scattering. Scattering takes place at a fixed point S at position r_s. r_t is the position of the physical transmitter. $r_u(t_k)$ denotes the position of the user equipment at time t_k with $k = 0, \ldots, \infty$. The position of virtual transmitter 1 is constructed by mirroring the physical transmitter position at the smooth surface. Virtual transmitter 2 is constructed at the position of the fixed point S, where the signal is scattered. A combination of scattering and reflection is also possible: the signal

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is first scattered at S and then reflected on the surface. Therefore, virtual transmitter 3 is constructed by mirroring the scattered signal at the surface [14].

With the emergence of 5G ultra-dense networks, co-operative positioning will be achieved through D2D communication over directional mmWave networks [13]. It will be used in wireless sensor networks and ultra-wide bandwidth networks. Observed TDoA accuracy is enhanced through D2D cooperative positioning. The user equipment, base stations, access points and any object capable of emitting and receiving radio signals are called nodes. In D2D cooperative localization, the nodes get their location information in relation to one another and can calculate their absolute position with the help of global reference information [15]. This method is suitable for short and medium range [13]. D2D communication will lead to high robustness and accuracy below one meter. The hybrid fusion of multiple sensors serves the same goal [1]. Smaller cells like picocells (range under 100 m) and femtocells (WiFi-like range) enable more accurate line of sight localization [15].

7. Future Research

(Statistical) machine learning will play an important role in future localization systems. With further research, machine learning technologies will be able to estimate missing or corrupted data. Machine learning has already been used for simultaneous localization and mapping. Heterogeneous networking protocols pose a challenge because they operate according to different standards and on different frequencies. Many different IoT standards such as Bluetooth, ZigBee, SigFox, LoRa, Narrow Band IoT exist. Research questions include how location services can remain accurate while switching communication protocols and how to make switching between the different standards efficient. 5G cellular network will rely on New Radio, which is a wireless access technology that was standardized in Release 15 of the 3rd Generation Partnership Project. It is mainly unexplored how characteristics of New Radio can be best utilized. Another research area is the limitations of low latency communication. Accuracy within centimeters will presumably be reached through ultra-reliable low latency communication. The UE will be able to send and receive messages within milliseconds [5]. Another open research topic for high data rate wireless systems are different beamforming schemes and the potential of beamforming for the improvement of the localization quality. Challenges of beamforming schemes are the uncertainty of parameters (for example channel states) and the non-convexity of the optimization [16].

8. Conclusion

5G enables more accurate location services. In this paper, different user localization use cases were explored. Fundamental network techniques like proximity, trilateration and fingerprinting were presented. Three different kinds of localization architectures were classified. After that, user localization in 4G cellular networks was briefly analyzed. Then this paper explored different features of 5G: mmWave technology, D2D communication and multipath-assisted algorithms like Channel-SLAM. These features will lead to centimeter level accuracy in user localization. While this development has many advantages, like better emergency response, it also leads us to the question of user privacy and data protection. With increasing technological possibilities to track user equipment with centimeter level accuracy, many questions about data privacy arise, like what data will be stored, where will the data be stored, for how long will the data be stored, who has access to the data, for which purposes is the data used, how is the data protected? These questions should be the topic of an ongoing public debate.

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