Survey of Cellular Mobile Radio Localization Methods: From 1G to 5G

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***Abstract*—Cellular systems evolved from a dedicated mobile communication system to an almost omnipresent system with unlimited coverage anywhere and anytime for any device. The growing ubiquity of the network stirred expectations to determine the location of the mobile devices themselves. Since the beginning of standardization, each cellular mobile radio generation has been designed for communication services, and satellite navigation systems, such as Global Positioning System (GPS), have provided precise localization as an add-on service to the mobile terminal. Self-contained localization services relying on the mobile network elements have offered only rough position estimates. Moreover, satellite-based technologies suffer a severe degradation of their localization performance in indoors and urban areas. Therefore, only in subsequent cellular standard releases, more accurate cellular-based location methods have been considered to accommodate more challenging localization services. This survey provides an overview of the evolution of the various localization methods that were standardized from the first to the fourth generation of cellular mobile radio, and looks over what can be expected with the new radio and network aspects for the upcoming generation of fifth generation.**

***Index Terms*—Cellular localization, standard location methods, positioning, cellular networks, 5G.**

I. Introduction

LOCALIZATION has been considered an optional feature in the standardization, implementation and exploitation of existing cellular networks. Nevertheless, the large cellular communication infrastructure deployed around the world can still be reused for positioning purposes, providing an added value to the network management and services. Thus, there has been relevant research contributions on positioning for each generation of cellular technology, from the first generation (1G) to the future fifth generation (5G).

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The introduction of time-division multiple access (TDMA) and code-division multiple access (CDMA) in the second generation (2G) of cellular standards was a breakthrough in mobile communications, such as with the Global System for Mobile Communications (GSM). Voice services could be exploited by mobile devices that were compatible with cellular networks within the same or different regions. The globalisation of cellular communications was then initiated with the creation of the Third Generation Partnership Project (3GPP) for the specification of 3G Universal Mobile Telecommunications System (UMTS), and its homologous for 3G cdma2000 systems, i.e., 3GPP2. Both consortiums of companies and institutions already considered several positioning methods in the standardization process. Their objective was to support emergency services and to exploit location applications. This interest has been preserved through the specification of the 4G Long Term Evolution (LTE), and it is expected to grow in the 5G standardization. As a result, there is an extensive literature on cellular radio localization of the mobile device or user equipment (UE), as well as applicable techniques and algorithms from other technologies, such as wireless local area networks (WLAN). However, most of the cellular networks only provide basic localization methods and assistance data for global navigation satellite systems (GNSS), as it is reported in [1]. The partial deployment of advanced cellular-based location methods is mainly due to the additional implementation costs incurred by the network operator.

The motivation of this survey is threefold. First we present the drivers to integrate cellular positioning into the cellular mobile radio standards. Second we survey the development of the location methods and its performances in the different generations that have been advanced from 1G till the recent evolution of the 3GPP LTE standard. We summarize the conclusions of the lessons learned of each generation. Last, we shed light on the topic of cellular positioning in order to pave the way for future developments in future releases of 3GPP LTE, such as Release 15 and beyond, to address future opportunities and requirements.

A. Emergency Services

The key drivers to determine the location of the mobile terminal in a cellular system have been governmental institutions. For instance, the Federal Communications Commission (FCC) of the United States (U.S.) defined enhanced 911 (E911) location requirements in the mid 1990s, and the European Commission (EC) formed, in the framework of harmonizing emergency services, the coordination group on access to location information by emergency services (CGALIES) in 2000. Both governmental institutions demanded to locate mobile terminals in case of an emergency call. The difference between both groups was the FCC acted with a legal mandate to enforce the objective, while the CGALIES just asked the cellular operators to cooperate. The consequence was an initiative led by standardization groups, such as 3GPP and 3GPP2, to determine the location of the mobile terminal. In the U.S., the operators could not fulfill the demands set by the FCC and were consequently fined. However, the operators disclosed the challenges to locate the mobile emergency caller and waivers were issued from the FCC. The demands were rediscussed during the 2000s as part of the 2G and 3G standards and finally resulted in refined requirements proposed by the FCC in the early 2010s. An extensive overview will be outlined in Section IV.

B. Localization Applications

The support for emergency services has mainly motivated the standardization of cellular localization. Nonetheless, the exploitation of the location information within the network has also attracted significant attention from operators and application developers. These localization applications can be exploited for commercial services or network optimization.

The location of the mobile device can be used to provide an additional functionality to the user, resulting in the so-called location-based services (LBS). These services can be exploited commercially by the network operator or the application developer, in order to obtain a revenue. Examples of such services are navigation, mapping, geo-marketing and advertising, asset tracking, social networking, augmented reality, location-sensitive billing, etc.

The location information can also be used for the network optimization, which is known as location-aware communications. This information is used to improve the communication capacity and the network efficiency. Example applications are network management, radio reconfigurable spectrum, intelligent transportation systems (ITS), vehicular ad-hoc networks (VANETs), resource management for device-to-device (D2D) communications, etc. This type of localization applications can be added to the self-organizing networks (SON) technology, which is a mechanism to ease and improve the operation of the network.

Although localization applications can result in direct or indirect economical profit, the network providers have been reluctant to invest on additional infrastructure, in order to improve the localization capabilities of the network. The extra cost associated to an improved positioning performance may be too high for the expected revenue. In addition, both user and network operator demand privacy of their location information for different reasons. The users privacy demands are a personal right, and are a current society concern, while the operators business is built on confidential information and on how the network is structured and organized.

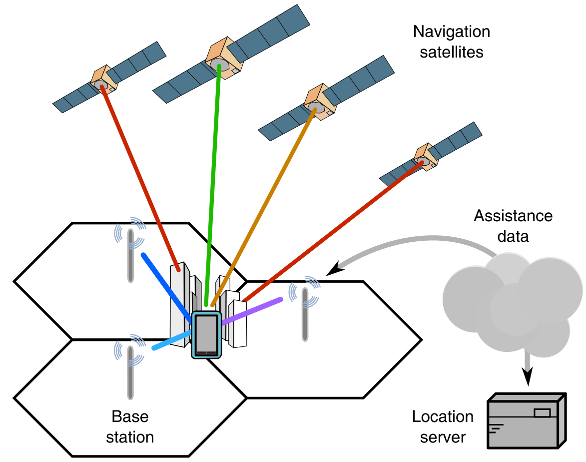


Fig. 1. General architecture of mobile- and network-based location systems in urban environments, considering a hexagonal cellular layout for the terrestrial network of BSs.

C. Structure of the Survey

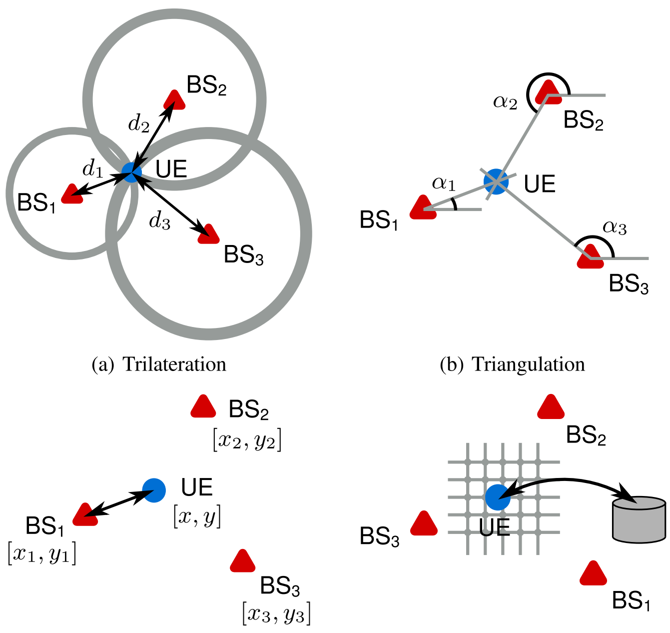
The survey is structured in seven sections. The fundamental positioning techniques and the existing surveys are reviewed in Section II. A historical review on the evolution of cellular localization from 1G to 4.5G is provided in Section III. This review also considers the main technical specifications (TS) and technical reports (TR) of the standards. The role of the governmental bodies on the standardization process is described in Section IV. The main contributions to the cellular location methods are reviewed in Section V, in order to assess their achievable positioning performance and their implementation limitations. The new research trends on 5G positioning and the lessons learned from the evolution of the cellular standards are outlined in Section VI. A summary is finally provided in Section VII.

II. LITERATURE

A. Fundamental Positioning Techniques

Positioning systems are designed to determine the coordinates of a certain object, while localization systems are aimed at placing these coordinates on a map. Nonetheless, both positioning and localization problems are often used as synonyms, when the system uses reference stations to accomplish the localization procedure, as in our case of interest depicted in Figure 1.

Positioning techniques used in cellular networks are based on fundamental localization principles. A receiver computes signal measurements with respect to single or multiple reference transmitters, and then calculates the position with a certain algorithm. As it is shown in Figure 1, the reference transmitters can be navigation satellites or cellular base stations (BSs). Satellite navigation is considered the main technology for localization, due to its global coverage and high accuracy. Cellular-based localization is used as a complementary solution, when there is a lack of satellite visibility due to the blockage of the satellite signals, which is typically the case in urban and indoor environments. Both downlink transmissions from BS to mobile device and uplink



(a) Trilateration (b) Triangulation (c) Proximity (d) Scene analysis

Fig. 2. Fundamental positioning techniques using radio signals.

transmissions from mobile device to BS can be used for this purpose. The positioning methods can be classified into two main categories depending on the entity that computes the position:

- *Mobile-based:* The (mobile) device itself calculates its location by using signal measurements from terrestrial or/and satellite transmitters. The assistance data from the network can be exploited to perform the signal measurements and the position calculation.
- *Network-based:* The network location server computes the position of the mobile device, by means of signal measurements performed by the network with respect to the mobile device, or signal measurements performed and sent by the mobile device to the network.

Mobile- and network-based wireless location have been adopted in cellular networks, with a predominance of the latter category on the current and next generation systems. The main reason is its centralized nature that allows full control of the location service by the network operator, as well as its support to legacy devices.

Regardless of the positioning method, different techniques can be used to compute the position of the mobile device, by considering different radio signal measurements or references. Figure 2 shows the fundamental positioning techniques that are classified as:

- *Trilateration:* The position solution is obtained by computing the intersection between geometric forms, e.g., circles or hyperbolas, created by distance measurements between the terminal and the reference transmitters or receivers. Several types of measurements can be used, such as time of arrival (ToA), time difference of arrival (TDoA) or received signal strength (RSS).
- *Triangulation:* The direction or angle of arrival (DoA or AoA) of the received signals is used to estimate the position by using the intersection of at least two known directions of the incoming signal.
- *Proximity:* The known transmitter position is assigned to be the position of the terminal. An example is the cell-ID method, where the position provided is the one of the serving base station. This is the most widely adopted method in conventional GSM networks.
- *Scene analysis:* Also known as fingerprinting or pattern matching, the algorithm is based on finding the best match for a certain signal measurement, such as RSS, time delay or channel delay spread, from a database of *fingerprints*. Each fingerprint is associated with a specific location.
- *Hybrid:* A combination of the previous localization algorithms can be implemented to improve the overall performance, or to support an algorithm that cannot be computed stand-alone given the lack of signal measurements.

B. Current Literature

Wireless location systems, not necessarily cellular-based, have been widely studied in the literature as it can be highlighted from the surveys in [2] and [3]. These surveys focused on the signal processing techniques, the network design, the fundamental limits and the radio technologies. An overview of the main surveys is provided in Table I, where cellular, WLAN and ad hoc networks are considered.

Our focus, instead, is on cellular mobile radio technologies. During the last 50 years, a new generation of cellular radio has been introduced almost every decade, from 1G to the future 5G. Although cellular networks have always been originally designed for communication purposes, some positioning capabilities were also present. The 1G mobile technologies were already applied for vehicle location, such as in [4], by using signal strength, time delay or DoA measurements. The introduction of the FCC E911 requirements encouraged the study of accurate localization in 2G cellular systems [5]. The challenges of these accuracy requirements are discussed in [6], and specifically reviewed for CDMA networks in [7] and for GSM networks in [8]. The implementation issues of E911 location networks are evaluated in [9], and the performance criteria are analysed in [10]. The 2G GSM location methods are further reviewed in [11], where the accuracy of circular, hyperbolic and mixed trilateration is geometrically analysed according to a typical cellular network deployment. The implementation of mobile- and network-based positioning methods in U.S. cellular networks is reviewed in [23], by focusing on uplink TDoA (UTDoA) methods with 2G GSM. A comprehensive review and comparison of the location technologies is provided for 3G in [12] and [13] and for 4G LTE in [25]. For instance, different location technologies are presented in [25] with a focus on various delivery methods in LTE networks. The different technologies are assessed and evaluated by various metrics, such as accuracy, impact on battery, network dependency, etc. An overall classification and description of the wireless positioning techniques (including cellular networks) is provided in [28]. The contribution in [29] describes the specification of the location methods, network architecture and location protocols for

TABLE I
OVERVIEW OF EXISTING SURVEYS ON WIRELESS LOCALIZATION

Survey	Year	Radio	Description
[4]	1977	1G cellular	Survey of vehicle location with 1G cellular networks.
[5]	1996	Wireless	Overview of commercial location systems and methods.
[6]	1998	2G cellular	Overview of the E911 location challenges and solutions with 2G systems.
[7]	1998	2G cellular	Review of the location accuracy impairments with 2G CDMA networks.
[8]	1998	2G cellular	Survey of the positioning techniques with 2G GSM networks.
[9]	1998	2G cellular	Review of the implementation issues of location technologies in 2G networks.
[10]	1998	2G cellular	Overview of the performance criteria to evaluate 2G location methods.
[11]	2001	2G cellular	Survey of trilateration techniques for 2G GSM localization.
[12]	2002	3G cellular	Comprehensive review of the 3G standard location methods.
[13]	2002	3G cellular	Survey of the 3G standard location methods.
[14]	2005	Cellular	Overview of the fundamental limitations of mobile positioning.
[15]	2005	Cellular/WLAN	Overview of network-based wireless location challenges and techniques.
[16]	2005	Wireless	Survey of signal processing techniques for wireless localization.
[17]	2005	UWB	Survey of performance bounds and algorithms for UWB positioning.
[18]	2007	Wireless	Survey of wireless indoor positioning techniques and systems.
[19]	2008	Wireless	Survey of positioning algorithms and theoretical limits for wireless networks.
[20]	2009	Wireless	Survey of indoor positioning systems for personal networks.
[21]	2009	UWB	Survey of cooperative localization techniques and their application to UWB networks.
[22]	2009	Wireless	Survey of ToA localization algorithms and NLoS mitigation techniques.
[23]	2009	Cellular	Review of positioning methods implemented in US cellular networks.
[24]	2012	GNSS	Survey of the challenges in indoor GNSS.
[25]	2013	4G cellular	Comprehensive review of the 4G LTE location methods.
[26]	2015	Wireless	Survey of signal processing techniques for indoor wireless tracking.
[27]	2016	Wireless	Survey of fingerprinting techniques for outdoor localization.
[28]	2016	Wireless	Survey of wireless positioning techniques for moving receivers.
[29]	2017	Cellular	Survey of standard cellular location methods from 2G to 4G.
[30]	2017	Cellular	Survey of prospective positioning architecture and technologies in 5G.

GSM, UMTS and LTE. The exploitation of the 5G disruptive technologies for positioning is discussed in [30]. However, there is no comprehensive review on the evolution and standardization process of cellular location methods from 1G to 5G. The existing contributions focus on the description of the positioning capabilities of cellular networks, but they do not highlight the key role of governmental bodies on the progress of cellular localization. Thus, this survey provides the main insights behind the specification of cellular location methods from past to present standards, their reported performance, and the localization perspectives in next-generation cellular networks.

III. CELLULAR MOBILE RADIO SYSTEMS

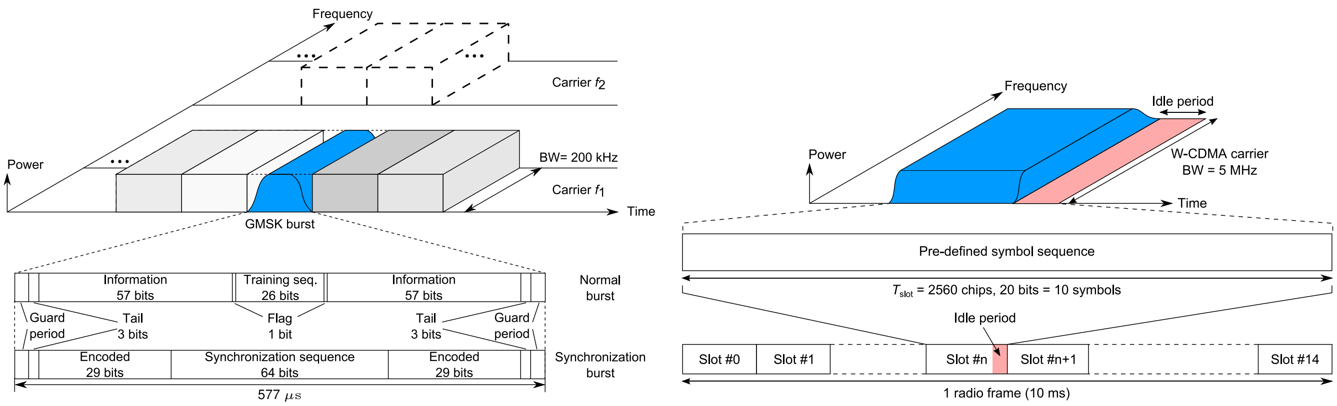
This section describes the evolution of location methods in the standardization of cellular systems, from 1G to 4.5G. The physical layer of these standards is briefly introduced, with special focus on the system bandwidth and the pilot signals. The role of governmental bodies on the adoption and enhancement of cellular localization is also reviewed.

A. 1G: Analog Systems

The mobile radio telephone appeared around the 1950s, but 1G cellular mobile radio networks were not introduced until the 1980s [31]. These cellular systems were based on analog technologies dedicated to provide speech services, where each call used a separated narrowband frequency channel. Several cellular standards were adopted in different regions [31], [32], such as Nordic Mobile Telephone (NMT), Advanced Mobile Phone System (AMPS) or Total Access Communications System (TACS), among others. These standards did not specify any positioning procedure, but vehicle location was already targeted to enhance the communication performance of cellular calls by means of system control [4]. For instance, cell site selection, speech channel allocation or handoff can benefit from the vehicle location, which were typically obtained with location methods based on the signal strength [33]. The 1G cellular systems were also used for intelligent vehicle highway system (IVHS) applications [5] or to support emergency services based on proprietary location solutions [6], such as Grayson Wireless with a joint TDoA and AoA solution or TruePosition with UTDoA, both using AMPS signals.

B. 2G: Digital Systems and the Case of GSM

Although the first commercial cellular system was introduced in 1969, the widespread use of cellular networks did not happen until the late 1990s [31]. One of the main enablers of this transition was the evolution of mobile communications, from many independent systems towards standard systems among countries. Such a commitment was first held in Europe



(a) GSM normal and synchronization bursts

(b) UMTS common pilot channel (CPICH) [34], [35]

Fig. 3. GSM and UMTS downlink pilot structures used for positioning.

by the *Conférence Européenne des Administrations des Postes et Télécommunications* (CEPT) in 1982 [32], which resulted in a common European cellular system in 1987 [36], later known as GSM. The development of the GSM standard was then driven by the European Telecommunications Standards Institute (ETSI) Special Mobile Group (SMG), which led to the first 2G digital cellular system globally adopted in the early 1990s. The choice of TDMA by GSM was followed by other digital standards [31], such as the digital AMPS (D-AMPS) or IS-54 [37] (later substituted by IS-136), the integrated dispatch enhanced network (iDEN) from Motorola, the personal digital cellular (PDC) in Japan, or the personal handy-phone system (PHS) in several Asian countries. As an alternative, the use of CDMA was first introduced by Qualcomm on the IS-95 standard [38], which was later called cdmaOne.

The physical layer of GSM is based on TDMA and frequency division duplex (FDD). As it is shown in Figure 3a, the Gaussian minimum shift keying (GMSK) modulation is used in a timeslot of 0.577 ms and a carrier spacing of 200 kHz, with optional frequency hopping (FH) and a frequency reuse between 1 and 18 [39, p. 7]. The main services are speech and circuit-switched data in macro cells, achieving a data rate up to 9.6 kbps [40]. The specification of GSM was divided in two phases. This allowed the fast deployment of common services during the first phase, such as telephony or short message service (SMS), and the introduction of technical improvements and additional services in the second phase. Still, there was no support for any positioning mechanism. Only two synchronization methods were specified for transmission purposes. In Phase 1, the radio subsystem synchronisation was included to improve handover transitions and to schedule user transmissions, by the round-trip time (RTT) perceived by the BS. The RTT resulted in the timing advance (TA) that the mobile device should apply to synchronize its uplink transmission. In Phase 2, the observed time difference (OTD) was added as an optional synchronisation feature, based on the time difference between BSs measured by the mobile device [41]. Since there was no location mechanism within the standard, the positioning capabilities of GSM were limited to the use of training or synchronization signals to compute ranging measurements, such as in [42]. Similar procedures were described for CDMA systems. For instance, the use of registration update messages in the IS-95A standard was proposed in [7] for time-based localization, called reverse link. These studies already indicated the need of synchronized BSs (i.e., optional for GSM and mandatory for IS-95) in order to implement the trilateration methods. As today, network synchronization was typically obtained with the Global Positioning System (GPS) [39, p. 8]. However, there was still a need to specify the positioning mechanisms within the standard for a successful implementation.

Although localization activities were introduced in the GSM standardization by 1995 [11], it was not until 1996 that a major step in cellular positioning took place. The FCC of the United States approved in [43] the provision of location requirements on 911 emergency calls, i.e., E911 services, which are described in Section IV. The E911 mandate motivated intensive efforts in United States to achieve the location requirements on the existing TDMA and CDMA cellular systems. As an example, several survey articles [6]–[10] reviewed the challenges and performance of cellular positioning in April 1998. The positioning techniques were mobile- or handset-based solutions, i.e., GPS, and network-based solutions, such as ToA, TDoA, AoA, cell-ID, fingerprinting or hybrid methods. In addition, assisted GPS (A-GPS) was introduced in [44] by SnapTrack (a company acquired by Qualcomm in 2000), where the GPS receiver is aided by the cellular network with the navigation message and differential corrections.

Meanwhile, digital cellular networks were evolving towards 3G mobile standards. ETSI members were developing the specification of both GSM Phase 2+ and UMTS. The GSM Phase 2+ defines general packet radio system (GPRS), known as 2.5G, and enhanced data rates for GSM evolution (EDGE), known as 2.75G, including packet-switched services, such as transport control protocol (TCP)/Internet protocol (IP). Since several regions began the standardisation of similar 3G technologies, the harmonisation of these specifications within one common framework was agreed. Thus, the 3GPP was created in 1998 as a partnership of international members to standardise the evolutions of GSM and UMTS, being ETSI one of the main sponsors and contributors [32]. In parallel, the 3GPP2 consortium was formed to continue the standardisation of IS-95 and cdma2000 technologies from the Telecommunications Industry Association (TIA) and the Electronic Industries Alliance (EIA). In 1999, the cooperation between ETSI and the American standardization group T1P1 resulted in the specification of the functional description of location services (LCS) in GSM [45] and in UMTS [46]. The positioning schemes specified in GSM were cell-ID and TA, uplink ToA, enhanced OTD (E-OTD), and A-GPS. The overall description of LCS in GSM [47] included requirements on location, response time, security and privacy, among others. Considering emergency services, the horizontal location accuracy was defined by local regulatory requirements, such as FCC E911, while there was no requirement for vertical positioning [47]. In 2000, the 3GPP became responsible for the specifications of the GSM/EDGE radio access network (GERAN), and its new features. However, the positioning support defined in [45] remains unchanged.

C. 3G: UMTS, cdma2000

The efforts to define 3G technologies already started in the late 1980s, e.g., with several European research programmes [39, p. 61]. In 1999, the International Telecommunication Union (ITU) finalised the specification of the International Mobile Telecommunications 2000 (IMT-2000) framework [48], in order to define an international standard for 3G cellular networks. The two main candidate technologies were UMTS and cdma2000 driven by 3GPP and 3GPP2, respectively.

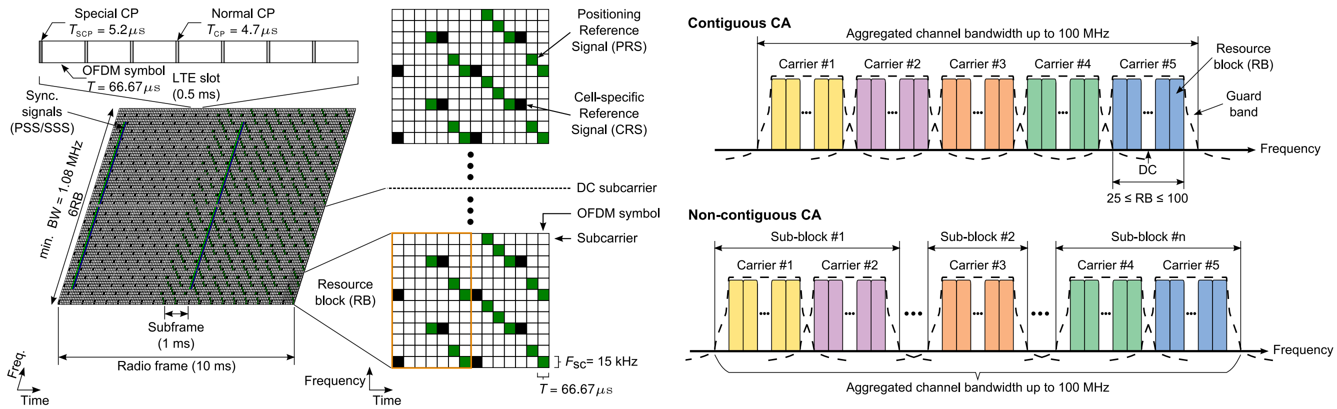
The main air interface of UMTS is wideband CDMA (WCDMA), which is called universal terrestrial radio access (UTRA). The UTRA network (UTRAN) operation is asynchronous, and FDD and TDD modes can be configured to achieve data rates up to 2 Mbps. The carrier spacing of WCDMA is 5 MHz, approximately, with a chip rate of 3.84 Mcps and frame length of 10 ms [39, p. 47]. In Release 99, the location methods defined in TS 25.305 [46] were cell-ID, observed TDoA (OTDoA) with network configurable idle periods in downlink (IPDL), and A-GPS. The OTDoA measurements are typically performed with the UMTS common pilot channel (CPICH), whose structure is shown in Figure 3b. In TR 25.847 [49], UE positioning enhancements were proposed. The description of LCS in TS 22.071 of Release 4 [50] were updated by supporting both GERAN and UTRAN, where the main services were enabled by a horizontal location accuracy between 25 m and 200 m. In Release 7 [51], uplink TDoA (UTDOA) was added to the supported methods in UMTS. RF pattern matching (RFPM) technologies were finally included in Release 10 of the UMTS standard [52], in order to improve the cell-ID positioning performance.

The cdma2000 technology is based on multiple narrowband CDMA carriers of 1.25 MHz, at a chip rate of 1.2288 Mcps [39, p. 433]. The network of BSs is synchronized, typically based on GPS. In 2001, the 3GPP2 produced the standard C.S0022-0 as a continuation of IS-801 (from TIA/EIA) to determine signalling of positioning services in CDMA systems [53]. The positioning technologies specified in this standard are advanced forward link trilateration (AFLT) and A-GPS, considering also the combination of AFLT and GPS.

D. 3.9G: LTE

The LTE technology leads the evolution of GSM and UMTS, as well as cdma2000, towards 4G cellular systems. Since the LTE standard in Release 8 and 9 is not fully compliant with the IMT-Advanced requirements for a 4G technology [56], as they are described in the following section, LTE is considered a 3.9G technology. Its air interface, called evolved UTRA (E-UTRA), is based on the orthogonal frequency-division multiple access (OFDMA) for the downlink and single-carrier frequency-division multiple access (SC-FDMA) for the uplink to achieve data rates up to 100 Mbps and 50 Mbps, respectively. This technology can operate in FDD and TDD modes with a system bandwidth between 1.4 to 20 MHz. Phase synchronization of the E-UTRA network (E-UTRAN) is only required for TDD [57] to be within 3 or 10 μs given a cell radius below or above 3 km, respectively.

The standardization development of LTE started in 2004 with proposals from the 3GPP consortium, such as the "Super 3G" concept of NTT DoCoMo [58]. But, it was not until December 2008 that the first specification of LTE was frozen by 3GPP with Release 8. By that time, the radio access network (RAN) #42 plenary approved in [59] and [60] the work items (WIs) of the LTE positioning service and the support for IP Multimedia Subsystem (IMS) emergency calls over LTE. The objective of these WIs was mainly based on providing a positioning protocol and a downlink terrestrial positioning method to act as a backup to A-GNSS, in regions where full visibility of GNSS satellites cannot be ensured and emergency calls are subject to strong regulation [61]. The downlink positioning method was suggested to be analogous to well-known techniques, such as E-OTD in GERAN, OTDoA in UTRAN, and AFLT in cdma2000. Following the evolution of UMTS, OTDoA positioning method was evaluated by RAN working group (WG) 1 and the positioning protocol was developed by RAN WG2 considering the performance requirements of RAN WG4. Focusing on the positioning method, Nortel earlier pointed out in RAN WG1 meeting #55 [62] that LTE positioning could support emergency services, but also, the user equipment location could help BSs to optimize RF deployment parameters, e.g., in the support of SON. In the following meeting (i.e., #55bis), the issue of neighbour cell hearability was introduced. As an evolution of the IPDL method in UTRAN, two main solutions were proposed by Qualcomm Europe in [63] and Alcatel-Lucent in [64]: a dedicated reference signal and the serving cell muting. In RAN WG1 meeting #56, simulation assumptions and performance evaluations were presented, such as by Alcatel-Lucent in [65] or by Ericsson in [66]. RAN WG1 meeting #56bis had many contributions on the topic, and the way forward on the definition of a positioning reference signal (PRS) allocated in a low-interference positioning subframe was agreed in [67], as it is shown in Figure 4a. Then, RAN



(a) LTE synchronization and reference pilots [54]

(b) LTE-Advanced and LTE-Advanced Pro spectrum [55]

Fig. 4. LTE downlink pilot structures used for positioning.

WG1 meetings #57 and #57bis served to specify the general definition of the PRS by selecting the preferred option among all the proposals. The PRS could be allocated in several positioning subframes, resulting in a positioning occasion to perform the reference signal time difference (RSTD) measurements. Several performance assessments could be found, such as in [68], [69], or [70]. For instance, in [70], system and propagation errors were also considered to assess the LTE positioning performance with a sensitivity analysis. The OTDoA specification was completed in RAN WG1 meetings #58 and #58bis. Finally, the LTE positioning support was defined in Release 9, at the end of 2009, by specifying the positioning methods within TS 36.305, i.e., enhanced cell-ID (E-CID), OTDoA with dedicated PRS, and A-GNSS, and the LTE positioning protocol (LPP) within TS 36.355. The LCS were described in the update of TS 22.071 [71], which supported GERAN, UTRAN and E-UTRAN.

E. 4G: LTE-Advanced

The 4G mobile communications systems are expected to fulfil the IMT-Advanced requirements in [56], such as peak data rates up to 1 Gbps at low speeds and up to 100 Mbps at high speeds. In order to fulfil these high data rates and mobility requirements, the 3GPP started the standardisation of LTE-Advanced (LTE-A) in Release 10 [72]. This evolution of the cellular system defines heterogeneous networks (formed by macro and small cells) whose demands are fulfilled by new features, such as carrier aggregation (CA), coordinated multipoint (CoMP) and advanced multiple-input multiple-output (MIMO) transmissions. The physical layer of LTE-A is backward compatible with LTE, using OFDMA for the downlink and SC-FDMA for the uplink. The LTE-A system bandwidth can reach up to 100 MHz [72]. The downlink resource allocation of the CA modes in LTE-A can be seen in Figure 4b. In addition, several positioning methods and enhancements were studied within the 3GPP standardization.

1) Network-Based Positioning: The standardisation of new positioning methods in LTE-A started with the study of network-based positioning in Release 10, i.e., UTDoA. The inclusion of UTDoA in LTE is mainly aimed at complementing A-GNSS in harsh environments and to support legacy UEs (i.e., Release 8) without downlink OTDoA capabilities. The measurements are performed by the LMU, which is specified in TS 36.111 [73]. This positioning method was studied following evaluation scenarios agreed in [74]. These scenarios included the use of uplink data and pilot signals transmitted by the UE, i.e., dynamic scheduling or semi-persistent scheduling (SPS) PUSCH transmissions with or without sounding reference signals (SRSs). Simulation assumptions were considered on the SRS configuration, interference and multipath models, and deployment parameters. A list of references within the UTDoA evaluation study can be found in [75]. Still, high-layer specifications for UTDoA could not be finalised by Release 10 [76], such as UE positioning architecture, protocol, interfaces or procedures. UTDoA was finally standardised by 2012 in Release 11 with some controversy, due to a dismissed lawsuit [77] between TruePosition (precursor of the UTDoA technology) and Ericsson, Alcatel-Lucent, and Qualcomm.

2) Radio Frequency Pattern Matching: RFPM or RF fingerprinting is an additional method that can be applied by using the RF signal measurements and positioning protocols (LPP and LPPa) already existing in LTE Release 9. The study on the inclusion of RFPM in LTE was proposed in Release 10 [78]. However, the resulting TR 36.809 [79] was not finalised until Release 12. This report complemented the current standard by providing simulation results on the positioning performance of RFPM. The signal strength and timing measurements used were already specified for E-CID in TS 36.214 [80] clause 5.1.15, i.e., intra-frequency reference signal received power (RSRP) and UE Rx-Tx time difference, respectively. The simulation methodology was described in [79], including simulation assumptions and error models. The report also provided two main improvements to the standard by obtaining these measurements in low-interference subframes (LIS), such as positioning subframes or almost blank subframes (ABS) in heterogeneous deployments, and using measurements from multiple radio access technologies (RATs), such as RF signal measurements from GSM and UMTS. This study led to the update of TS 36.305 [81] with the inclusion of inter-RAT measurements from GSM and UMTS systems.

3) Positioning Enhancements: Positioning enhancements for the methods defined in Release 9 were proposed in [82], resulting in the study summarized in TR 36.855 [83], which was conducted by RAN WG4 during Release 12 and finalised in Release 13. This study assessed the feasibility to improve the performance requirements of the OTDoA and E-CID positioning methods in LTE-A scenarios. These requirements included the update of the minimum ranging performance for every system bandwidth in TS 36.133 [84], as well as the granularity of the reporting measurement. The 3GPP consortium proposed three main positioning enhancements. First, the multi-antenna transmission diversity of the PRS could be exploited by combining the PRS occasions from two antennas. Second, heterogeneous networks formed by macro cells and small cells, such as remote radio heads (RRHs) or low power nodes (LPNs), could improve the hearability of the PRS. Since the RRHs can have the same identification as the macro cell, several solutions to identify the transmitter were reported, such as the use of PRS muting or different PRS subframe offsets. Third, multiple serving cells in CA or CoMP could be used to improve the E-CID positioning performance.

F. 4.5G: LTE-Advanced Pro

The further enhancements of the LTE standard from Release 13 onwards are known as LTE-Advanced Pro [85]. This evolution is formed by key features to further increase the mobile broadband and connectivity performance, including the key role of indoor positioning, but maintaining full backward compatibility with LTE-A, as it is shown for the downlink spectrum in Figure 4b. In Release 13, the 3GPP consortium approved in [86] a study item on indoor positioning enhancements for UTRA and LTE, reported in TR 37.857 [87]. This study was mainly addressed due to the stringent indoor location requirements proposed by the U.S. FCC in the E911 mandate [88]. In addition, the FCC requested to prioritize any study item on positioning enhancements in the 3GPP standardization process [89]. Thus, RAN WG1 and RAN WG4 working groups presented many contributions to improve the existing positioning techniques depending on the radio access technology, i.e., RAT-dependent, such as OTDoA, UTDoA, E-CID and RFPM, or RAT-independent, such as A-GNSS, terrestrial beacon systems (TBS), WiFi/Bluetooth-based positioning and barometric pressure sensor positioning. The deployment scenarios and evaluation methodologies were agreed, and simulation results were provided for the existing technologies, including the study of 3D channel models for LTE [90]. These simulation results demonstrated the possible fulfilment of the 50-meters horizontal location accuracy required by the E911 FCC with LTE location methods. The main potential enhancements for 3GPP LTE positioning technologies were reported in [87] and [91].

- *OTDoA enhancement:* current OTDoA specification could be enhanced with more density in the time domain, PRS bandwidth extension (above 20 MHz) using CA, new PRS pattern, combination of cell-specific reference signal (CRS) and PRS, transmission of PRS in unlicensed bands (LTE-U), or high hearability in CoMP scenarios with more small cells.
- *D2D-aided positioning:* anchored UEs with known position could cooperate with target UEs to improve their location accuracy, by using neighbour UE location or using ranging and signal strength measurements. Part of these measurements could be reused from the discovery framework, or physical sidelink discovery channel (PSDCH), adopted in Release 12 [92].
- *MIMO:* vertical positioning could be enhanced with multiple antennas and beamforming techniques, called elevation beamforming/full dimension (EB/FD) MIMO.
- *WLAN/Bluetooth:* ranging and signal strength from WLAN and Bluetooth networks could be combined with LTE-based measurements for positioning, by using inter-RAT functionalities, such as the WLAN interworking in TS 23.234 [93].
- *TBS:* beacon signals or PRS could be transmitted with a dedicated infrastructure in order to enhance the positioning capabilities.
- *Barometer:* the inclusion of support to barometric sensors could improve the vertical accuracy, such as by providing weather conditions and reference points.

The 3GPP standard finally specified TBS, barometric pressure sensor positioning, WLAN positioning and Bluetooth positioning within Release 13 of TS 36.305 [95]. In addition, accuracy requirements for ranging or RSTD measurements were also updated depending on the use of received signals at the same carrier frequency, i.e., intra-frequency measurements, or at different carrier frequencies, i.e., inter-frequency measurements. The RSTD accuracy requirements specified in Release 13 are summarized in Table II, given a subcarrier signal-to-interference-plus-noise ratio (SINR) of the reference and neighbor cells greater than −6 dB and −13 dB, respectively [94]. These requirements are noted in terms of the minimum LTE sampling period, i.e., $T_s = 32.55\,$ns, and in meters for the minimum PRS bandwidth in resource blocks (RB), which corresponds to a bandwidth of 12 subcarriers equal to 180 kHz. As it can be noticed, the inter-frequency requirements are worse than the intra-frequency requirements. This is because the standard already considers the time-delay errors implied on the switch between two carrier frequencies performed by the same RF front-end [96]. Furthermore, these requirements do not limit the computation of ranging measurements in dense multipath. As it is shown in Figure 5 with

TABLE II
RSTD ACCURACY REQUIREMENTS FOR INTRA- AND INTER-FREQUENCY MEASUREMENTS IN RELEASE 13 OF TS 36.133 [94]

Minimum PRS bandwidth	Accuracy (T_s)		Accuracy (m)	
	Intra	Inter	Intra	Inter
$\geq$ 1.08 MHz (6 RB)	±15	±21	±146.5	±204.9
$\geq$ 2.7 MHz (15 RB)	±10	±16	±97.6	±156.1
$\geq$ 4.5 MHz (25 RB)	±6	±10	±58.6	±97.7
$\geq$ 9 MHz (50 RB)	±5	±9	±48.8	±87.8
$\geq$ 13.5 MHz (75 RB)	±4	±8	±39.0	±78.1

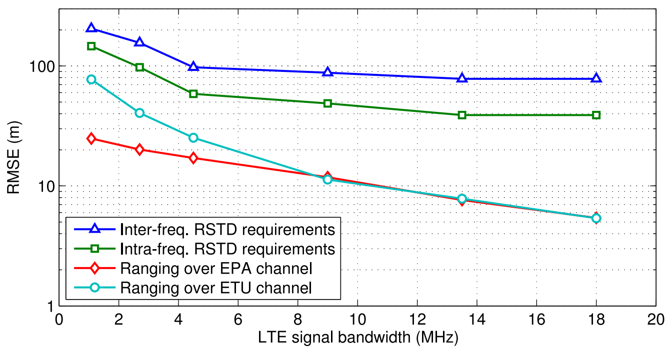


Fig. 5. Achievable ranging performance over EPA and ETU channel models, and RSTD requirements in Release 13 of TS 36.133 [94].

the root-mean-square error (RMSE) of the time-delay estimation, a threshold-based ranging estimator (with time-delay estimation limits $\tau \in [-T_s, T_s]$) can fulfil these requirements over multipath with low delay spread, i.e., Extended Pedestrian A (EPA) model, and high delay spread, i.e., Extended Typical Urban (ETU) model. The location requirements for LCS were updated in TS 22.071 [97] according to the horizontal and vertical accuracy required by the local regulatory bodies.

The evolution of LTE-A Pro is aimed at providing a new candidate technology for 5G. Further enhancements on the positioning capabilities, latency reduction, Internet of Things (IoT), i.e., LTE-M or narrowband IoT (NB-IoT), or ITS, among others, are examples of key features under study in Release 14 [85].

IV. Role of the Governmental Bodies

The role of the governmental bodies is manifold. It ranges from defining the spectrum allocation for each cellular operator for its own services to dedicated services for the government. A key driver for the performance of localization was and still is nowadays the determination of the caller location for emergency services. This localization service is not charged by operators. The ability to localize the caller is demanded by governmental bodies, such as the FCC in the U.S. In the following we will review the activities of governmental bodies, mainly by the FCC and some activities of the European Commission. The activities of these legal bodies are outlined in Figure 6 and 7. In the following we revise in detail the motivations and consequences of the FCC and the EC to improve location services in cellular networks.

A. FCC (United States)

The FCC of the United States specified the rules on the application of E911 services to ensure fast assistance of the wireless 911 caller. The location of the caller is the key E911 requirement. In 1996, the FCC approved for the first time a national mandate for E911 services [43]. With this a new service class, the location-based services, that would go beyond the E911 services was initiated. The definition of E911 services for cellular networks started in 1996 and evolves till today.

In 1996, the deployment of the new E911 services should be achieved in two phases with the following milestones:

- *Phase I:* By the end of 1997, operators were required to provide a caller's automatic number identification (ANI) and the location of the BS or cell site receiving a 911 call to the designated public safety answering point (PSAP), which is called automatic location identification (ALI).
- *Phase II:* By 1 October 2001, operators were required to provide the location of a 911 caller, with a root-mean-square error (RMSE) of 125 m in 67% of all cases.

The implementation of E911 services by the cellular operators was acknowledged by the confirmation of the FCC that the originally set performance values were not achievable. Consequently the demanded fines from the cellular operators for a penalty fee was changed and the operators received waivers. Nonetheless, as a result of the technological improvements after the adoption of the initial rules, the FCC decided to distinguish between positioning methods, since mobile-based or hybrid solutions were more accurate and reliable than network-based solutions. Thus, in 1999, the accuracy requirements were revised in FCC 99-245 [98] for mobile- or handset-based solutions:

- 50 m for 67% of calls,
- 150 m for 95% of calls, and

for network-based solutions are:

- 100 m for 67% of calls,
- 300 m for 95% of calls.

Operators using mobile-based solutions were asked to provide the location capabilities by 1 October 2001, reaching 95% of their customers by 31 December 2005. The operators considering network-based solutions should provide the caller location information (i.e., ALI) to 50% of their coverage or population by 1 October 2001, and 100% by 1 October 2002. Due to the tight requirements and the incompatibility of mobile-based solutions with legacy phones, the FCC provided waivers to several companies on the application of this E911 mandate in 2001 and 2002 [99]. Hence, the FCC supervised the implementation of E911 services and approved in 2007 a stricter order of the original Phase II standard. The location accuracy and reliability requirements had to be fulfilled at the PSAP local region by 11 September 2012 [100]. With this order the operators could not achieve the Phase II requirements by averaging locations across the entire national network.

The E911 location requirements were improved again in 2010 [101] by considering the PSAP-level compliance. The E911 Phase II location accuracy to be fulfilled within eight years from the order [101] is for mobile-based solutions:

- 50 m for 67% of calls,
- 150 m for 90% of calls, and

for network-based solutions:

- 100 m for 67% of calls,
- 300 m for 90% of calls.

The FCC created, by 19 March 2011, the Communications Security, Reliability and Interoperability Council (CSRIC) III WG3, in order to mainly address E911 location accuracy testing. The CSRIC III WG3 tested, during winter of 2012–2013, the indoor location accuracy of three technologies: network

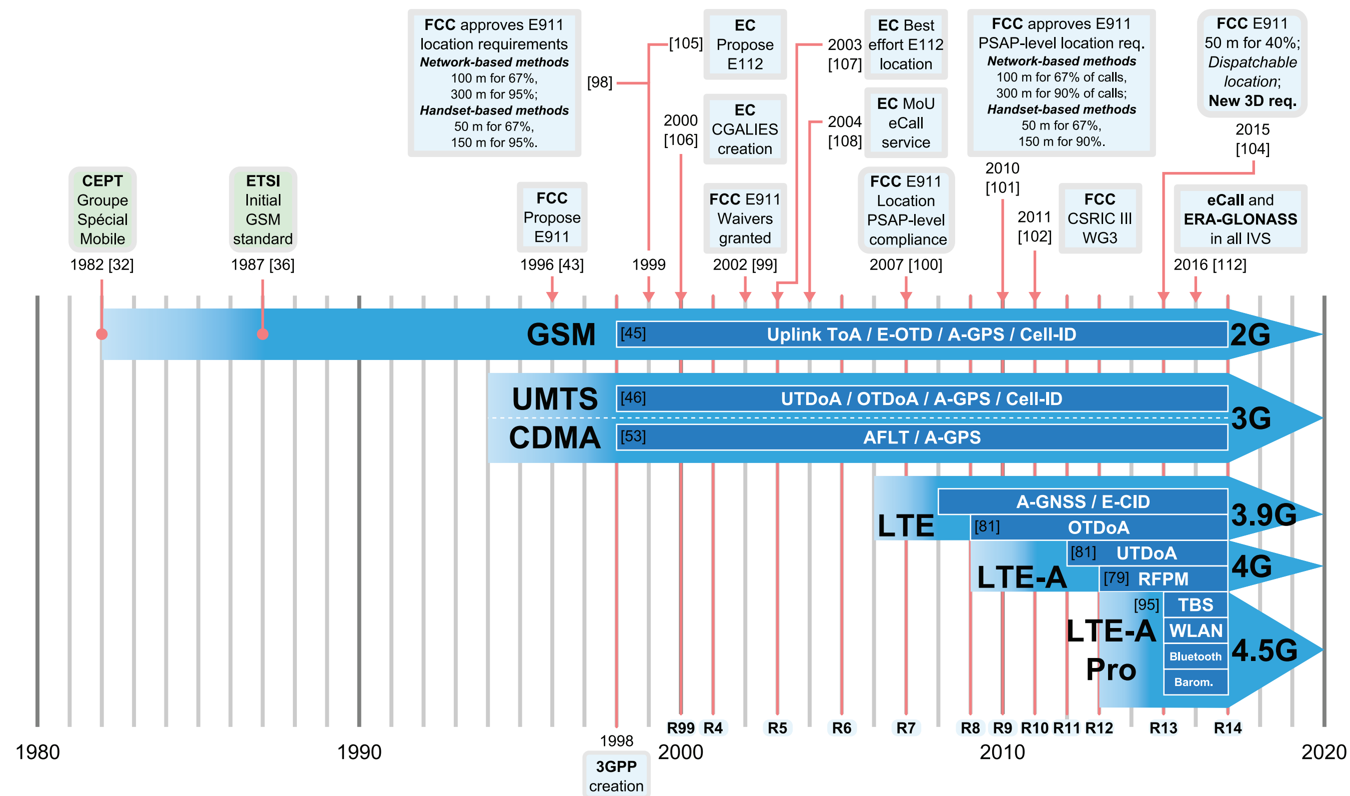


Fig. 6. 40-years timeline of the cellular localization standards, methods and legal mandates.

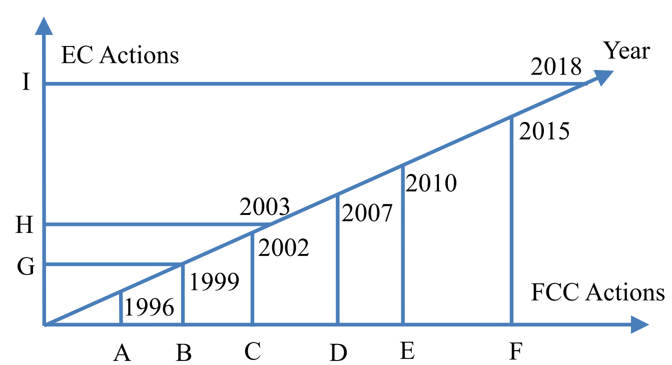


Fig. 7. Timeline of the demands on improving location performance in cellular networks in the U.S. by the FCC and in Europe by the EC. A: Propose call location for E911 services. B: Approved E911 location requirements. C: Waivers granted for U.S. operators. D: E911 PSAP-location compliance. E: Revised E911 location requirements. F: Including 3D location requirements for indoor positioning. G: Proposed call location for E112 services. H: EC defines best effort for E112. I: Proposed start of eCall service in vehicles.

beacons by NextNav, RF fingerprinting by Polaris Wireless, and hybrid A-GPS and AFLT by Qualcomm. According to the resulting report in [102], these technologies proved a relatively high yield and different levels of accuracy in indoors for dense urban, urban, suburban and rural environments. This report suggests future improvements by means of the deployment of LTE PRS ranging and its hybridisation with A-GNSS. The same testbed was also used in [103] to demonstrate the fulfilment of the E911 location requirements with a hybrid A-GPS and UTDoA solution from TruePosition. In 2014, the FCC proposed in [88] specific measures to regulate indoor location, such as by requiring 50 m of horizontal accuracy and 3 m of vertical accuracy for 67% of 911 calls. In line with the work and study items proposed for indoor positioning within the 3GPP standardization, the FCC urged the 3GPP to complete these items [89]. In 2015, the FCC finally regulated three-dimensional (3D) indoor location for E911 emergency calls [104], by introducing the following main location requirements:

- *Horizontal location:* provision of dispatchable location, i.e., building address, floor level, and room number of the caller, with an horizontal accuracy of 50 m for the 40%, 50%, 70% and 80% of the wireless 911 calls within 2, 3, 5 and 6 years, respectively,
- *Vertical location:* provision of uncompensated barometric data (when available) to PSAPs within 3 years, and deployment of dispatchable location or z-axis technology fulfilling a vertical accuracy metric (to be proposed and approved).

In FCC 15-9 [104], reporting and compliance measures are also required, such as live 911 call data in certain cities and their surrounding areas, as well as a limit to time-to-first-fix (TTFF) of 30 seconds. In parallel, the E911 Phase II location accuracy is still expected to be fulfilled by January 2019 [104]. The regulation for emergency services is focused on network operators, but mobile hardware and software companies can also provide emergency location services, such as Google within Android operative systems.

B. EC (Europe)

Following the motivation of enhanced emergency services in the United States, the European Commission filed in 1999 a report requiring to the operators, the provision of location information of 112 callers (emergency service number in Europe), i.e., enhanced 112 (E112), by 1 January 2003 [105]. The plan coincided with the roadmap of the Galileo system to establish a new GNSS for outdoor applications.

The regulation of E112 continued in Europe with the CGALIES, created by the European Commission in May 2000. This coordination group is a partnership between members of the public and private sector that aims at assessing feasible location requirements and solutions for E112. Although location accuracy requirements were described by CGALIES in [106], the European Commission recommendation of 25 July 2003 in [107] did not mandate specific location performance, but it encouraged the providers to use their best effort to ensure E112 services. For this purpose, the European Memorandum of Understanding (MoU) for the realisation of an interoperable in-vehicle emergency call service (eCall) was presented in 28 May 2004 [108]. In order to support this legislation, the European Commission have continuously called for European research projects in order to support the eCall programme. For instance, the European mobile integrated location system (EMILY) project investigated the hybridisation of terrestrial (2G and 3G) and satellite-based GNSS positioning, as it described in [109] and the references therein. Another example is the wireless hybrid enhanced mobile radio estimators (WHERE) project, funded by the European Commission, aimed at enhancing 4G communications by using location information [110]. The follow-on project WHERE2 [111] exploited synergies between heterogeneous cooperative positioning and communications in cellular networks.

The European Commission has required full deployment of the eCall in-vehicle system by 31 March 2018 [112], which affects new models of passenger cars and vans. A status of mobile positioning for emergency services, such as eCall, in European cellular networks is provided in [1], where cell ID methods were widely deployed, A-GNSS was clearly favoured, and the deployment of OTDoA PRS was not envisaged.

C. Russian Federation

Similar to the eCall system, the Russian Federation is developing the ERA-GLONASS in-vehicle system [113], [114]. ERA-GLONASS is envisaged to be fully compatible with the eCall system in Europe and therefore, a bilateral agreement between the EC and Russia has been approved.

V. Cellular Localization Methods and Reported Performance

In this section, we outline in detail and classify the reported performance of standardized cellular positioning techniques, which were introduced in Section II. The AoA method has not been considered, because it has not been specified in any cellular system yet. This complements Section III, which presents the evolution of the cellular communication standards themselves. The methods are typically based on a two-step procedure, i.e., first to obtain signal measurements and then to use these measurements to compute the mobile radio position. In the following we will present several location methods that make use of common communication network features. The terminology is different between the different cellular generations, however, the basic concepts behind are similar. Therefore, we classify these basic concepts for the different generations in Table III as follows:

- Proximity
- Scene analysis
- Trilateration
- Hybrid

The location methods under review are classified among technology generation, type of localization and category (i.e., mobile- and network-based). A general 67%-location accuracy of the horizontal and vertical position is assigned to each method by considering the cited references. The expected horizontal location accuracy of the location methods is shown in Figure 8 for indoor, outdoor urban and rural scenarios. The following sections will describe each localization method that is currently applied in cellular networks.

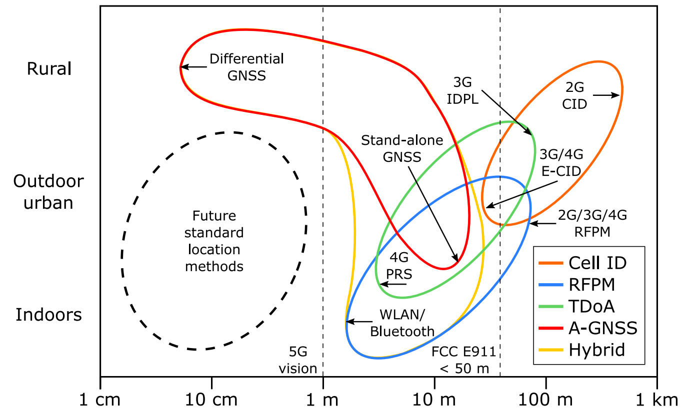


Fig. 8. Expected horizontal accuracy of cellular mobile radio localization methods for indoor, outdoor urban and rural scenarios.

A. Challenges of Trilateration-Based Localization

The use of trilateration-based positioning may result in a sufficient accuracy to fulfil legal mandates. However, several sources of ranging errors need to be considered, as it is described in [12], [13], and [133].

- *Coverage:* The transmit power and the number of BSs mainly define the cost of the network deployment. Cellular networks are primarily designed for communications, thus the cell coverage is optimized to reduce the number of deployed BSs to serve a certain service area. The coverage is affected by the local environment that results in path loss, shadowing and multipath fading, which bounds the achievable ranging accuracy. Both, the coverage and the location of the BSs, impacts the dilution of precision (DOP) for the position computation, which depends on the geometry between available BSs and mobile radio device. Nevertheless, cellular signals are typically received well above the noise floor, and mobile users might be commonly surrounded by BSs, where

TABLE III
CLASSIFICATION OF LOCATION METHODS STANDARDIZED IN CELLULAR SYSTEMS

Methods	**Technology**	**Type**	**Category**	**67%-loc. accuracy** Horizontal (meters)	Vertical (floors)	**References**
CID+TA/CID+RTT	2G, 3G, 4G	Proximity	Network	> 100	–	[115], [116], [117], [118]
E-CID	3G, 4G	Proximity	Network	~ 50	1 to 3	[87], [119], [120]
RFPM	2G, 3G, 4G, WLAN, Bluetooth	Scene analysis	Network	> 50	1 to 2	[18], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130]
Uplink ToA	2G	Trilateration	Network	> 100	–	[131], [132]
UTDoA	3G, 4G	Trilateration	Network	< 50	–	[103], [124]
E-OTD	2G	Trilateration	Mobile / Network	> 100	–	[8], [11], [133], [134], [135], [136]
AFLT	3G	Trilateration	Mobile / Network	> 50	–	[137]
OTDoA	3G, 4G	Trilateration	Network	< 50	≥ 3	[87], [119], [133], [136], [138], [139], [140], [141], [142], [143], [144], [145], [146], [147], [148], [149], [150], [151], [152], [153], [154]
A-GNSS	2G, 3G, 4G	Lateration	Mobile / Network	~ 10	≥ 3	[44], [155], [156], [157], [158]
TBS	4G	Trilateration	Mobile / Network	< 50	1 to 2	[87], [102]
Barometer	4G	Sensors	Mobile / Network	–	~ 1	[120], [159], [160], [161], [162]
Hybrid	2G, 3G, 4G	Hybrid	Mobile / Network	< 10	1 to 2	[141], [158], [163], [164], [165], [166], [167], [168], [169]

e.g., the geometric center between four BSs provides the optimum horizontal DOP.

- *Inter-cell interference:* In cellular networks the reuse of frequencies is essential to ensure the efficient usage of the operators spectrum. Consequently cellular systems are interference limited. The serving BSs introduce inter-cell interference over neighbour BSs in conventional cellular networks, due to single-frequency transmission. In addition, the transmit power is optimized depending if the user is at the cell edge or at the center of the cell. The position can be successfully estimated by the TDoA-based trilateration if the mobile radio receives signals from three or more BSs. However, only at the cell edge a good reception of several BSs is concurrently ensured. This limitation is due to the near-far effect or hearability problem, where the nearest BS masks the neighbour BSs. In LTE-A, CoMP and eICIC are introduced to improve the data throughput in heterogeneous networks. However, macro and small cells still overlap their transmission in certain scenarios, such as hotspots by using the same cell ID. Typical positioning solutions to reduce the inter-cell interference are based on the use of blank or mute transmission periods, such as PRS muting in LTE, at the expense of a reduction of the network capacity.
- *Multipath:* In urban and indoor environments cellular systems operate with multiple base stations to cover the needs of several mobile radios. However, the signals are blocked, diffracted and reflected by the environment, which may also change dynamically. This results in a time-varying multipath channel that degrades the communication and positioning performance. However, the multipath effects are more deleterious for positioning purposes due to the stringent time-delay estimation constraints, such as under non-line-of-sight (NLoS) conditions. The reason is that a reduced signal bandwidth limits the resolvability of the individual multipath components. For example, a bandwidth of 10 MHz limits the resolvability of individual multipath components to 30 m. Under NLoS conditions, an additional bias affects the ranging estimation. Therefore, the impact of the bias on the estimation performance can be reduced by determining and weighting the LoS and NLoS conditions of the propagation channel accordingly.

- *Synchronization:* Trilateration requires a precise estimation of the distance between transmitters and receiver. Therefore, the unknown synchronization errors of the involved clocks on both ends affect the position accuracy. In cellular networks this results in an extra deployment of reference stations or network synchronization procedures. Typical solutions are based on GNSS receivers or Precision Time Protocol (PTP) mechanisms [170]. These implementations should consider tight synchronization in order to avoid any physical delay [133]. The following standards, 2G GSM, 3G UMTS and 4G LTE-FDD, did not specify any synchronization requirements for time or phase accuracy [170], in contrast to 3G cdma2000, 4G LTE-TDD and LTE-A. Especially, with the recent advances in communications to enable carrier aggregation or coordinated multipoint transmission or reception, the requirements for synchronization have increased [171]. However, the synchronization requirements for trilateration-based positioning methods are at least one order of magnitude lower than those requirements for communications. As a rule of thumb, the network provider should consider a BS synchronization below 100 ns for TDoA-based positioning [96]. In this sense, the network synchronization error defined in [87] follows a truncated Gaussian distribution with a range of timing errors between ± 100 ns and a variance of 50 ns. The simulation results in [87] show a reduced impact of this synchronization error of up to 3 m. Weiss *et al.* [172] discussed the synchronization issues for current and future communication systems. They identified that a key factor of the performance of the oscillator is its cost and its integration into the radio device. In recent years, the prices of (temperature compensated or controlled) quartz crystals have been sinking together with an enhanced performance. The costs range from several U.S.-cents for an accuracy of 10^{-6}s to several thousands of U.S.-Dollar for an accuracy of 10^{-12}s.

B. Challenges of Indoor Localization

Current cellular networks are able to provide connectivity to mobile devices located indoors and outdoors. However, they are not designed to perform accurate indoor localization with cellular signals. Conventional cellular deployments are based on macro-cell layouts tailored to serve minimum communication requirements with a single BS. Thus, their cellular-based location methods can only provide coarse positioning in indoors, due to the high signal attenuation, rich multipath and inter-cell interference.

Given the challenges of indoor cellular localization, most widely-adopted methods are based on proprietary solutions or technologies. On the one hand, fingerprinting techniques are typically implemented in WLAN systems [15], [18], [20], [26], to take advantage of their dense indoor deployments. The positioning performance of these techniques depends on the precision of the fingerprinting database and the location algorithm, whose computational complexity can be reduced by empirical models and tracking techniques [173], [174]. The WLAN fingerprinting solutions have an average horizontal position accuracy between one and five meters [18], [26]. On the other hand, high-accuracy positioning can be achieved with dedicated deployments of beacons, such as those based on UWB with sub-meter level accuracy [17]. These proprietary deployments can allocate a large signal bandwidth for the specific indoor coverage, in order to obtain precise ranging measurements. However, the main disadvantage of these proprietary solutions and technologies is the additional cost required to implement the dedicated infrastructure.

The indoor location requirements mandated by the FCC in [104] has certainly triggered the efforts to enhance indoor positioning with cellular networks, as it is studied in [87] and discussed in Section III-F. The standard solutions are based on the exploitation of heterogeneous networks, by using cellular signals from macro and small cells, D2D communications, multi-antenna techniques and additional positioning technologies, such as TBS, WLAN, Bluetooth and barometers. The main limiting factors of indoor cellular localization are the lack of synchronization of indoor small cells and the rich multipath environment. The following sections describe the reported performance of standard cellular location methods in indoors and outdoors.

C. Cell ID-Based

Cell ID (CID) is the most popular positioning method in cellular networks. The location of the mobile device is assigned to the geographic location of the serving BS. The accuracy of this cell coverage method can be improved by additional information, such as the cell sector, ranging measurements, i.e., TA (timing advance) in GSM [45] and RTT (Round Trip Time) in UMTS [46], and signal strength measurements, i.e., RXLEV (reception level) in GSM and received signal code power (RSCP) in UMTS.

The CID method can be directly applied in any cellular network, without requiring any extra resources. Thus, the cell ID-based method is considered as a *fall-back* or *back-up* positioning procedure, in case other methods cannot be applied. The main drawback is the coarse accuracy achieved, which is limited by the cell size and the resolution of the TA for GSM, which is a bit period equal to 554 m, or the resolution of the RTT for UMTS, which is a chip period equal to 78 m (without any oversampling). Experimental results show in [115] a location accuracy above 100 m, even by combining CID with TA and RXLEV. Similar trial results are obtained by using signal attenuation measurements and general path loss models in [116]. The use of RTT measurements from three BSs is assessed in [117] by forcing soft-handover in UMTS. However, a more realistic scenario is considered in [118] by using only one BS. The experimental results with RTT measurements in UMTS commercial networks show a radial accuracy between 70 m and 90 m for 67% of the cases [118].

D. Enhanced Cell ID

The E-CID method was specified in Release 9 of LTE [81], and later included also in Release 10 of UMTS [52], as an improvement of the CID method. This method combines the cell coverage with additional measurements, such as AoA, timing (TA or RTT) and signal strength measurements.

Simulation results with LTE networks in [119] show Rx-Tx time difference errors below 50 m for a signal bandwidth higher than 5 MHz, which are limited by the granularity of the ranging measurements in multiples of the minimum LTE sampling period T_s (i.e., 9.77 m). Considering the simulated heterogeneous networks in [87], the E-CID method can achieve horizontal and vertical location accuracy within 50 m and 10 m, respectively, for a dense deployment of indoor small cells. Experimental results in [120] show a probability of floor-level detection of 70% with the CID method for an indoor femtocell deployment. The E-CID performance can be further improved with cooperative techniques based on the proximity detection of anchor UEs, as it is shown in [87] by means of D2D-aided positioning.

E. RF Pattern Matching

One of the most common location methods implemented in wireless networks is RFPM or fingerprinting [27]. Although these methods do not require any changes on the standard network, they need a database of signal fingerprints associated to a geographic position. Typically a fingerprint of a certain geo-location is associated with a signal measurement, such as the RSS, to find the mobile device. The position accuracy of this method depends on the calibration of the database and the quality of the location-dependent measurements.

Fingerprinting methods were already implemented in GSM [121] to enhance the position accuracy over CID. Considering a dense network of BSs in an urban environment, the database correlation method (DCM) is shown in [121] to achieve position errors of 44 m in the 67% of the cases with trial results. However, 2G cell radius or inter-site distance (ISD) may typically be in the order of kilometres, thus RSS-based fingerprinting methods fail to fulfil the FCC E911 Phase II requirements of 1999, as it was assessed with the CRB in [122]. The problem of large cells may be overcome, as proposed in [123], by using TA and RTT measurements, whose accuracy is less dependent on the cell size than RSS measurements. Nonetheless, in indoor environments, the horizontal location accuracy was above 100 m, as in the case of Polaris Wireless technology in the CSRIC III testbed [124]. GSM-based fingerprinting was also studied for floor-detection inside buildings in [125], with a measurement campaign conducted during 2005 and 2006. Considering a tall building scenario, the floor was correctly detected in 60% of the cases [125], by using RSS measurements from up to 29 GSM channels, instead of only using the 6-strongest cells, such as in [121]. Thus, Varshavsky *et al.* [125] recommended the inclusion of floor identification in E911/E112 specifications, with a vertical accuracy within two floors of error for 95% of the cases.

In UMTS, fingerprinting methods are also applied by using RSCP measurements of the CPICH from the serving and neighbour BSs. In [126], the pilot correlation method (PCM), which is based on the least-squares minimization of the power-delay profile (PDP), is tested with field measurements, achieving 70 m and above 150 m for the 67% of cases in a dense urban network and in a large macro cell network (i.e., average ISD of 1.2 km), respectively.

RFPM methods have been studied for LTE-A in TR 36.809 [79] for urban and suburban scenarios, i.e., ISD equal to 500 m and 1732 m, respectively, including GSM and UMTS inter-RAT measurements. Using a maximum likelihood estimator and standard measurements, e.g., RSRP and UE Rx-Tx measurements, the results show positioning errors around 100 m for the 67th percentile and higher than 200 m for the 95th percentile in urban and suburban environments, considering 10 MHz system bandwidth and 10 m of bin spacing. The 3D localization has also been studied and validated with fingerprinting techniques by using A-GPS and LTE simulated measurements in [127] and field measurements in [128].

The communication between UEs can also be exploited for RFPM methods, as it is described in [129]. D2D communications for proximity-based services (ProSe), studied in Release 12 [175], can be used to exchange signal measurements between UEs, in order to improve the RFPM positioning by using cooperative algorithms.

The use of inter-RAT measurements, such as LTE and WLAN fingerprints from heterogeneous networks, has been proposed in [130] within the Self-organized Heterogeneous Advanced RadIo Networks Generation (SHARING) project funded by Celtic-Plus cluster. This proposal was validated with field measurements of signal strength, showing positioning errors below 50 m for the 67th percentile of the occasions. In addition to the validation with these measurements, this project proposed the enhancement of the inter-working LTE and WLAN capabilities in [93] for SON functionalities, such as the minimization of drive tests (MDT). Since Release 13 of TS 36.305 [95], WLAN and Bluetooth positioning methods based on fingerprinting are supported, in order to further enhance indoor localization. These methods have been widely adopted in commercial applications, and their horizontal position accuracy is generally below 10 m in indoors [18].

F. Uplink ToA

The uplink ToA positioning method was specified in 1999 within the GSM standard [45]. This method is based on the time-delay estimation of uplink transmissions, which can be the access bursts defined for asynchronous intra-cell handover, or the control channel periodically transmitted in idle mode. The ranging measurements are computed by LMUs, which may be stand-alone units or integrated in the BSs. These signal measurements are used by the serving mobile location center (SMLC) to calculate the user position by trilateration. The SMLC has access to the coordinates of the BSs and the synchronization among them, which is defined by real-time difference (RTD) values.

As it is discussed in [131], uplink ToA suffers by the same limitations as other trilateration methods, such as limited cell coverage, DOP, inter-cell interference, multipath and synchronization. In [132], simulations results for a GSM and IS-136 networks show location errors above 100 m for the 67% of the cases in an urban environment.

G. Uplink TDoA

The UTDoA method was specified in Release 7 of UMTS in 2005 [51] and in Release 11 of LTE-A in 2012 [176]. This method is the counterpart of uplink ToA in GSM. Ranging measurements are computed based on the uplink signals of the mobile device by LMUs placed at known locations. In LTE, these uplink signals are usually the SRS, and the network requests (to the eNodeB scheduler) to allocate the maximum SRS bandwidth available. But, the LMUs can also exchange snapshots of the uplink data signals with dynamic scheduling or SPS, in order to compute their cross-correlation. The UTDoA measurements are then transferred to the location server, where the mobile position is calculated. Thus, this method is compatible with legacy mobile devices.

The positioning capabilities of UTDoA technology in UMTS networks were shown by TruePosition in [103] for simulated emergency calls in a real deployment, using commercial off-the-shelf (COTS) smartphones and the existing AT&T 3G UMTS network. Similarly to the CSRIC III campaign in [124], the testbed compared UTDoA with a hybrid solution between A-GPS and UTDoA, which selected each technology depending on the best accuracy achieved. The results show positioning errors below 50 m for both solutions under the 67th percentile of the calls. TruePosition claims in [77] to have implemented LMUs at approximately 90,000 cell sites within AT&T and T-Mobile networks.

H. Enhanced Observed Time Difference

The E-OTD method is a trilateration positioning method specified in GSM [45], as an extension of the OTD synchronization method. The mobile device computes TDoA, called OTD, measurements between the signals transmitted from different BSs. These pilot signals are usually the broadcast control channel (BCCH) and the synchronization channel (SCH), whose bursts are less frequent than those of BCCH. The correlation of the corresponding training sequence is used to estimate the OTD measurements in idle or communication modes. Since GSM networks are typically asynchronous, LMUs at known fixed positions compute RTD measurements between BSs. The geometric time difference (GTD) stands for the propagation between BS and mobile device, which is obtained by compensating RTD from OTD measurements. The mobile device can calculate its position through broadcast assistance data, i.e., RTD values and BS coordinates. However, the mobile device can also provide the ranging measurements to the network, where the SMLC computes the user location.

Early trials using this technique with GSM signals obtained an average accuracy of 151.2 m in an urban environment [8]. The positioning performance is mainly limited by the low signal bandwidth. The extra deployment cost of LMUs for network synchronization can be reduced by using multiple receivers in a cooperative approach [134]. The impact of the geometric dilution of precision (GDOP) between the location of the BSs and the mobile device is assessed in [11]. However, multipath is certainly the major source of ranging errors, producing a critical degradation in GSM [133]. Experimental measurements on different environments in [135] show typical position errors between 50 m and 500 m, where most of the error contribution is due to multipath. Thus, E-OTD has failed to fulfil the E911 accuracy requirements [136].

I. Advanced Forward Link Trilateration

The AFLT location method was specified in 1999, first for IS-901 system, and later for IS-95 CDMA and cdma2000 by 3GPP2 [53]. Similarly to E-OTD, AFLT is based on the time-difference measurements between pilot signals from serving and neighbour BSs. Nonetheless, the position can be computed at the mobile device, because CDMA networks are synchronized to the GPS time with an accuracy of 100 ns. Thus, the AFLT method can be easily implemented at the mobile device in CDMA networks, without any additional infrastructure. In addition, the standard allows authorized mobile devices to send the ranging measurements to the location server, where the position is computed with additional synchronization corrections.

The main advantage of the AFLT method is the low-complexity implementation due to the built-in network synchronization. However, serving and neighbour BSs transmit on the same time and frequency, resulting in an increase of the near-far or hearability problem. In addition, since cdma2000 signals have a low bandwidth, the resulting AFLT accuracy is above 50 m, as it is shown in [137] with experimental measurements for a stand-alone receiver.

J. Observed TDoA

The OTDoA positioning method is defined in UMTS as the counterpart of E-OTD in GSM, being also standardized in 1999 [46]. The user position can be computed at the mobile device with assistance data or at the SMLC, in both cases, by using the ranging measurements obtained from the primary CPICH signals. In addition, UMTS specifies the IPDL method in order to reduce the inter-cell interference on the OTDoA measurements. This method consists on muting the transmission of certain BSs at certain periods to increase the hearability of the pilot signals. In case the network of BSs is not tightly synchronized, the UMTS standard also solves this problem by adding LMUs to the network in order to compute the RTD measurements [46].

The four main limitations for accurate OTDoA positioning in UMTS are multipath, the hearability problem, the geometry of BSs and the network synchronization, which results in an extra cost of the network deployment [133]. As an alternative to overcome the positioning complexity from using LMUs and capacity loss by the IPDL, the cumulative virtual blanking (CVB) technique is proposed in [138], which uses snapshots of the baseband signal captured at the UE and BSs for interference cancellation. Using this technique within the SMLC, trial results in a rural UMTS network show an OTDoA positioning accuracy of 20 m [138]. However, OTDoA has not been deployed in any commercial UMTS network, since carriers were already expecting in 2011 [136] to migrate directly to the LTE technology.

As an evolution of UMTS, the LTE standard specified the OTDoA method in 2009 [81]. The ranging measurements are computed by the mobile device using dedicated pilot signals for positioning, i.e., PRS. These signals have high configurability in terms of power, time and frequency allocation, including muting patterns to reduce inter-cell interference. Considering COTS mobile devices, the computation of the position is restricted to the enhanced SMLC (E-SMLC), which has access to the BSs coordinates and the time synchronization between BSs.

Academic and private studies have assessed the performance of LTE OTDoA. Ericsson AB in [139] uses field measurements to estimate the LTE PRS ranging performance. The results show an LTE OTDoA positioning accuracy better than 20 m for 50% of the cases and 63 m for 95% of the cases, using the PRS over a bandwidth of 20 MHz. LTE PRS-like signals with a sampling frequency of 20 MHz are used in [140] and obtained an indoor location accuracy below 30 m. Mensing *et al.* [141], [142] evaluated the performance of TDoA in urban environments with and without GPS close to the BS and at the cell edge of the BS. Especially for mobiles close to the BS, the TDoA performance is significantly reduced by inter-cell interference. Within the WHERE project, interference cancellation techniques were proposed for LTE [143] to exploit multiple links from different BSs. The proposed technique based on the secondary synchronization channel (S-SCH) increases the hearability of the neighboring cells especially close to the serving BS and improves the performance significantly, by achieving a positioning accuracy of 100 m for the 70% with respect to a 30% without using interference cancellation. The achievable localization accuracy of the LTE PRS is assessed in [144] and [145], resulting in a position accuracy around 10 m in multipath channels with a 20 MHz system bandwidth. Most of these contributions mainly use threshold-based or first-peak estimators, such as in [119], due to their low complexity. Advanced multipath mitigation techniques have also been proposed by using joint maximum likelihood (JML) time-delay and channel estimators in [146], or with a subspace-approach in [147]. The performance of LTE-A Pro OTDoA positioning has been assessed with simulations by the 3GPP consortium in [87]. The results show a horizontal accuracy within 50 m for 80% of the attempts. The vertical accuracy is higher than 10 m (i.e., around 3 floors), although it can be improved with a high number of small cells. OTDoA positioning can be enhanced with D2D cooperative techniques, as it is discussed in [87] and [148]. The new positioning enhancements proposed for LTE-A are assessed in [149]. A cooperative location algorithm is studied for LTE-A heterogeneous networks in [150], where their tracking algorithm achieves a position accuracy around 10 m in indoor environments with femtocells. Simulation results on 3D positioning with LTE are provided in [151], with position errors below 7 m for the 90% of the cases.

The LTE ToA positioning performance has also been evaluated with cellular signals of opportunity. In [152] and [153], the CRS is used to obtain field ToA measurements, resulting in a location accuracy below 21 m in outdoors [152] and below 8 m in indoors [153] for the 50% of the cases. Vehicle and aerial LTE field measurements are also obtained opportunistically with the CRS in [154], whose results show a RMSE of the ToA-based position of 9.32 m.

K. Assisted GNSS

Assistance data of GNSS systems is provided within the GSM [45], UMTS [46], CDMA [53] and LTE networks [81] to aid the GNSS receiver embedded in most mobile devices. The assistance data can be formed by [155]: accurate timing, satellite Doppler shift, coarse position of the mobile device, navigation message, or differential corrections from a reference receiver, i.e., differential GNSS. The main advantages of this external data (provided by the cellular network) are a significant reduction of the TTFF, a reduced battery consumption, and a high sensitivity (being able to acquire GNSS signals with 25 dB of attenuation) [44].

Although the A-GPS and A-GNSS methods were supported in 2G, 3G and 4G, performance requirements were not introduced until Release 6 of UMTS [177] and Release 9 of LTE [178], respectively. The A-GNSS position calculation can be performed at the mobile device or at the location server. As it is proposed in [156] and [157] based on the *Matrix* concept, the position and timing assistance can also be provided autonomously within the mobile device, by using other cellular-based location methods. Field measurements in [44] and [156] show horizontal location accuracy around 10 m in open sky and light urban conditions. Experimental results in indoors show vertical location errors above 10 m (similar to three floors) with a stand-alone GPS solution [158].

L. TBS (Pseudolites)

The TBS method has been specified in Release 13 of LTE [95]. This method is based on a network of ground stations that transmit dedicated positioning signals, in order to complement GNSS in indoor and urban environments. The standard supports spread spectrum signals (i.e., GNSS-like signals) with TDMA for near-far mitigation, which are based on the metropolitan beacon systems (MBS) defined by NextNav. Thus, these ground-based transmitters can be considered pseudolites operating at different frequency bands than GNSS. The PRS-based TBS transmission is considered part of the OTDoA method in Release 14 of LTE [179].

The positioning performance of the MBS technology is assessed within the CSRIC III WG3 indoor testbed [102]. The results show a horizontal indoor accuracy around 50 m for the 67% of the cases in urban and rural environments, and a median vertical accuracy of approximately 2 m. In [87], the TBS technology was simulated with GNSS-like signals by NextNav and Broadcom and with LTE PRS-like signals by Qualcomm, resulting in a horizontal accuracy below 50 m for the 90% of the cases, and a vertical accuracy above 20 m for the 40% of the cases.

M. Barometer

The barometric sensor method has also been specified in Release 13 of LTE [95] for the determination of the floor level in indoors. The use of barometric pressure measurements has been widely studied in the literature, such as in [159] and [160], resulting in a vertical positioning accuracy below one meter. Since this method is sensitive to local pressure conditions, additional pressure measurements from other sources can be used at the mobile device or location server [95]. Further improvements on the indoor vertical positioning can be achieved by using inertial sensors or magnetometers, such as in [161] and [162]. Field measurements within an experimental LTE femtocell network in [120] show a floor detection above 90% of the cases.

N. Hybrid

The hybrid solution is based on the combination of multiple standard positioning methods. The most common hybridization is the fusion of cellular trilateration methods with GNSS. Since the GNSS satellite visibility is severely degraded in urban environments due to blockage of the LoS signal, the cellular ranging measurements are used to complement the GNSS method.

Nevertheless, the standards do not provide specific hybrid algorithms to compute the position. These hybrid solutions are left for proprietary implementations in every network. Recommendations for minimum requirements with hybrid solutions can only be found in the 3GPP2 standard for CDMA systems in [180], where hybrid AFLT and A-GPS solutions are required to provide horizontal location accuracy of 100 m and 175 m for 67% and 95% of the cases, respectively. Hybrid location systems have been commercially deployed in U.S. networks, such as hybrid A-GPS and AFLT in [12] and [124], and hybrid A-GPS and UTDoA in [103].

Several nonlinear Kalman filters (KFs) are used in [163] with simulation and field trials to compute the hybrid GPS and GSM solution with TA and RXLEV measurements, resulting in horizontal errors around 70 m. Fields measurements conducted within EMILY project show the improvement on the localization availability by hybridising E-OTD or OTDoA measurements with A-GNSS in [164]. Angelis *et al.* [165] propose the loosely-coupled integration of GNSS and 2G/3G networks, by either using the satellite- or cellular-based position fix depending on the availability. Considering a distance-dependent NLoS model, the simulations results show a position accuracy of 37 m for 90% of the cases with a cell radii of 200 m [165]. A hybrid solution between A-GPS and OTDoA with W-CDMA signals is simulated in [166], resulting in a slight improvement of the position and velocity estimation. The hybridisation of GNSS and LTE OTDoA measurements was studied in the WHERE project [141]. Considering ray-tracing models, simulations results in [141] showed a horizontal position accuracy below 10 m with a hybrid GPS, Galileo and LTE solution, by means of nonlinear KFs. An evaluation methodology for hybrid multi-GNSS and LTE positioning is proposed in [167], also resulting in a horizontal positioning accuracy below 10 m with field GNSS observables and simulated LTE measurements. In [158], a hybrid GPS and pseudolite is experimentally tested in indoors and outdoors to achieve a horizontal position error below 5 m and a vertical position error between 1 and 2 floors. This pseudolite system is similar to the TBS specified in LTE-A Pro [87]. Furthermore, simultaneous localization and mapping (SLAM) techniques have been presented as advanced hybrid location algorithms, such as in [168] and [169], in order to combine multiple cellular and wireless technologies.

VI. The Evolution Towards 5G

5G technology is expected to revolutionise the communication and positioning aspects of next-generation cellular mobile radio. 5G systems are aimed at fulfilling the recommendation of IMT for 2020 and beyond in [181]. This recommendation targets three main usage scenarios with specific capabilities and requirements:

- *Enhanced mobile broadband (eMBB):* wide-area coverage and hotspots for seamless user experience and high throughput.
- *Ultra-reliable and low latency communications (URLLC):* high throughput, low latency and high availability.
- *Massive machine type communications (mMTC):* very large coverage and number of connected low-cost devices with a very long battery life.

Indeed, high positioning accuracy is also a key requirement within the 5G vision. For instance, the automotive industry envisages a location accuracy as low as 10 cm for self- or assisted-driving applications [182], [183], or enhanced services defined in [184] expect an accuracy below 10 m for 80% of the occasions and below 1 m for indoor deployments. In this context, the 3GPP consortium defines a set of use cases to be supported in the future [185], where the positioning accuracy is one of the potential requirements. New technologies are expected to provide the necessary means to achieve these performance requirements, such as optimized waveforms, wide bandwidth, massive MIMO, millimetre wave (mmWave), D2D or high-density networks. Although the positioning support may not be considered a priority on the 5G standardization process, its significance is expected to notably increase due the forward-compatible nature envisaged within the future 5G standard, being even considered in 3GPP Release 15. For instance, high-accuracy vehicular positioning can benefit from these 5G disruptive technologies [186]. This section provides a summary of the new research trends on 5G positioning, and the lessons learned from previous generations towards 5G standardization.

A. New Research Trends on 5G Positioning

Recent research contributions have initiated the study of 5G technologies for positioning purposes. On the one side, location-awareness is a key feature of 5G aimed at enhancing the communication performance. A review of the benefits of location information is provided in [187] for each layer of the protocol stack. On the other side, dedicated network and signal designs can boost the achievable positioning capabilities in 5G, as it is studied in [188] and [189]. Indeed, the design and exploitation of future 5G cellular networks has triggered new research trends within the topic of cellular radio localization. Given the new technical features within 5G, previous and innovative works on wireless location technologies can be adopted for the first time in cellular networks. The main research trends are classified here.

1) Millimetre-Wave Massive MIMO: The use of mmWave and a massive number of antennas is one of the main revolutions in 5G. These features allow the generation of highly directional beams between transmitter and receiver, while the high attenuation losses limit the number of arrival multipath reflections, resulting in LoS conditions for most of the cases. Fundamental bounds on position and orientation of massive MIMO systems are derived in [190] and [191], confirming achievable position accuracy below one meter. The uplink RSS measurements are used in [192] with fingerprinting-based techniques and distributed massive MIMO arrays for positioning. Their results show a RMSE of the mobile position around 35 m with RSS measurements from only one BS. Still, further research is necessary on the exploitation of this promising technology.

2) Multipath-Assisted Localization: Wideband signals are a key feature to achieve accurate positioning, as it has been widely studied in UWB systems [17], because multipath can be mostly mitigated due to its resolvability. However, multipath components of the channel impulse response can also be exploited for localization. A new research trend is based on the use of the multipath components (MPC) for positioning, with advanced tracking algorithms [193] or by considering the signal reflectors as virtual transmitters [194]–[196]. For instance, multipath-assisted techniques can be used for assisted living [195], e.g., medical assistance or emergency services, where a single transmitter is used to locate the mobile device indoors. These innovative techniques are able to achieve high-accuracy localization at the centimeter level [195].

3) Device-to-Device Communication Enables Cooperative Positioning in Ultra-Dense Networks: The direct communication between mobile devices and the existence of a high density of small cells paves the way for the application of cooperative positioning. As it has been studied in wireless sensor networks (WSN) and UWB [21], the cooperation between nodes can result in a high accuracy and robustness. In addition, the adequate resource allocation between users themselves can enhance the positioning performance, as it is studied in [197]. Thus, cooperative positioning with D2D communications in ultra-dense 5G networks is expected to achieve seamless or ubiquitous positioning with accuracies below one meter, in addition to the use of high bandwidth, high carrier frequencies and beamforming techniques to reduce NLoS bias, as it is shown in [198]. Ultra-dense 5G networks can also be exploited with relatively narrow bandwidth by combining ranging and angle measurements, as it is shown in [199] and [200]. Their simulation results show a position accuracy below one meter at the 95% of the cases for a signal bandwidth below 10 MHz, by using a joint ToA and DoA algorithm and using one or two base stations in an urban 5G ultra-dense network.

4) Hybrid Fusion of Multiple Sensors: The combination of 5G communications with multi-sensor technologies, such as inertial sensors, camera or GNSS modules, is expected to support innovative applications, such as mobile cloud sensing [201], massive automotive sensing [202], or cloud GNSS positioning [203]. Indeed, cloud GNSS signal processing, whose concept was early demonstrated in [204] based on the transmission of GNSS signal snapshots for remote processing, can now be widely adopted and implemented, in order to enable advanced positioning applications [203], such as security and authentication, integrity monitoring, or jammer detection. In addition, the hybrid fusion of 5G radio localization and various multiple sensors is also of special interest to achieve high-accuracy and robust positioning.

B. Lessons Learned

The 5G technology is envisaged to provide intrinsic features to notably enhance the achievable positioning capabilities of future cellular networks, such as ultra-wideband signals, tight network synchronization, ultra-high density of BSs, or narrow beam transmission. Thus, the deployment of accurate positioning methods may not require additional infrastructure. In addition, the positioning support is expected to have a key role in the 5G forward-compatible standard, in order to fulfil the positioning requirements of 5G applications. These requirements vary with different level of position accuracy, robustness or availability, depending on the application. Thus, the network design can be tailored to accomplish the corresponding communication and positioning requirements. This section provides ten potential lessons learned from the past standardisation processes of cellular mobile systems to consider positioning in 5G networks.

1) GNSS: The 5G standard is expected to support any positioning method available within the mobile device or the network. Still, their deployment will be subject to a minimal implementation cost. In this sense, GNSS will have a key role in terms of network synchronization and mobile device localization, as it has been in previous generations. This is due to the wide adoption, global coverage and high performance of GNSS in outdoor environments. Thus, the 5G positioning standard should continue to provide assistance data, such as extended ephemeris, precise corrections for precise point positioning (PPP), or reference observables from GNSS stations for differential GNSS. In addition, the 5G standard should support authentication methods for GNSS, in order to enhance the GNSS protection against potential threads, such as jamming and spoofing.

2) Indoor Positioning: The focus of the location of mobile radio users has changed (with respect to the first generations) from mostly outdoors to indoors. Therefore, also the specifications of hybrid or complementary positioning methods to GNSS need to adapt. Proprietary positioning solutions, such as fingerprinting methods, are expected to be adopted without any impact on the physical-layer standardization. In order to provide alternatives to third-party solutions, cellular-based indoor positioning methods should be supported, by considering the specific scenario conditions.

3) Heterogeneity: Next-generation networks are not expected to consider a preferred cellular-based location method within the standard. They should be flexible enough to determine the appropriate method, in order to adapt to the network needs. Nonetheless, AoA and its combination with ranging estimates is expected to achieve a very high position accuracy. This is due to the introduction of mmWave massive MIMO, which should operate most of the occasions with a very high bandwidth in LoS conditions. However, this advanced technology is not expected to be deployed at every element of the network. Thus, there may be a predominance of cellular ranging-based methods for accurate positioning, in addition to GNSS and hybrid methods. Proximity methods are expected to be considered as back-up methods, or to be used only when coarse localization is required.

4) Synchronization: One of the critical aspects for the deployment of cellular ranging-based location methods, e.g., OTDoA, UTDoA or TBS, is the network synchronization, which should be in the order of nanoseconds to provide accurate positioning. Thus, this aspect should be considered in the specification of tight network synchronization requirements in future cellular standards, in order to support ranging-based methods. In this sense, the GNSS-based procedures are the main candidate to fulfil these synchronization requirements in outdoor environments. The use of accurate RTT or advanced network time protocols should be considered for indoors. Further, the chosen waveform will impact the synchronization requirements with a potential benefit for location methods [171].

5) Interference: Another important aspect is the need for the standardization of interference-avoidance schemes for localization. Initial mechanisms to counteract the hearability problem between stations within OTDoA methods were specified in UMTS [46]. A dedicated positioning signal was finally specified in LTE, in order to further enhance the OTDoA location accuracy, and a positioning protocol was included. However, the current schemes defined for OTDoA positioning methods, i.e., the PRS muting mechanism, may not be sufficient for a network with a very high number of heterogeneous nodes. Thus, the standard should include new resource allocation mechanisms for positioning purposes, in order to allow accurate ranging measurements in next-generation networks.

6) Power Consumption: GNSS modules with low power consumption are currently commercialised for IoT devices. Nonetheless, some mMTC applications are expected to demand a very stringent power consumption and a relaxed position accuracy. Thus, complementary location methods should be specified for narrowband transmissions, as it is currently studied for NB-IoT [85].

7) Cooperative Positioning: Independently of the location method, cooperative positioning protocols could exploit the high density of synchronous and asynchronous nodes in future heterogeneous networks. Although preliminary work has been initiated within D2D communications, the exchange of location information between mobile devices, small cells and BSs needs to be enhanced, in order to allow the deployment of cooperative positioning techniques in the whole network, such as for vehicle-to-vehicle (V2V) applications. Thus, the standard should include a cooperative protocol within the network elements, in order to enhance the resource allocation and location information sharing for positioning and communications purposes.

8) Device-Centric and Network-Centric: Most cellular-based location methods rely on a network server to solve the mobile device position. This is due to the confidential treatment of the network information by the operators, such as BS locations and network synchronization. However, this limits the implementation of certain positioning methods, such as mobile-based OTDoA, and their hybridisation with local sensors. For instance, the latency of the position calculation is very important for applications that require an immediate response at the mobile device, such as mission-critical applications. In this sense, the standard should introduce secure mechanisms to support both mobile- and network-based positioning methods, when downlink and sidelink signals are used.

9) Network Planning: The network planning, such as BS placement or power allocation, should also be based on the potential positioning capabilities of cellular-based location methods. In this sense, the resource allocation should be optimized for both positioning and communication purposes. Thus, the future standard should support a dynamic allocation able to maximize the data throughput and the achievable positioning capabilities, when required by a certain application.

10) Commercial Exploitation: Last but not least, there has been a significant interest for location-based services in existing cellular networks. However, the additional infrastructure required in certain positioning methods has limited their deployment and exploitation. This trend is expected to change in 5G, because its advanced network features can boost the cellular-based positioning capabilities without additional investments. Thus, it is up to the operators and vendors to exploit cellular mobile radio localization as a profitable business in next-generation networks.

VII. Summary

This survey provides a detailed overview of the cellular mobile radio localization methods, their reported performance, drawbacks and strong points, from the first generation (1G) towards the fifth generation (5G). The evolution of these cellular location methods is reviewed for each generation of standards. The trilateration and hybrid location methods have shown the best performance according to the literature review. In addition, governmental bodies have reinforced the need for complementary cellular-based location methods. However, the network providers are still reluctant to assume the costs implied on the implementation complexity of this kind of methods, a trend that may change in the future with the inherent technological improvements of future 5G networks. This survey has also outlined the new research trends on 5G positioning, as well as the lessons learned from previous generations. This outlook envisages a promising perspective of 5G location methods, still the standardization bodies need to consider the positioning support as a key aspect of cellular network design.

List of Acronyms

1G	First Generation
2G	Second Generation

3G	Third Generation
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
4G	Fourth Generation
5G	Fifth Generation
A-GPS	Assisted Global Positioning System
ABS	Almost Blank Subframes
AFLT	Advanced Forward Link Trilateration
ALI	Automatic Location Identification
AMPS	Advanced Mobile Phone System
ANI	Automatic Number Identification
AoA	Angle of Arrival
BCCH	Broadcast Control Channel
BS	Base Station
CA	Carrier Aggregation
CDMA	Code-division Multiple Access
CEPT	*Conférence Européenne des Administrations des Postes et Télécommunications*
CGALIES	Coordination Group on Access to Location Information by Emergency Services
CID	Cell Identity
CoMP	Coordinated Multipoint
COTS	Commercial Off-the-shelf
CPICH	Common Pilot Channel
CRS	Cell-specific Reference Signal
CSRIC	Communications Security, Reliability and Interoperability Council
CVB	Cumulative Virtual Blanking
D-AMPS	Digital Advanced Mobile Phone System
D2D	Device-to-device
DCM	Database Correlation Method
DoA	Direction of Arrival
DOP	Dilution of Precision
E-CID	Enhanced Cell Identity
E-OTD	Enhanced Observed Time Difference
E-SMLC	Enhanced Serving Mobile Location Center
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
E112	Enhanced 112
E911	Enhanced 911
EB/FD	Elevation Beamforming/Full Dimension
EC	European Commission
eCall	In-vehicle Emergency Call
EDGE	Enhanced Data rates for GSM Evolution
EIA	Electronic Industries Alliance
eMBB	Enhanced Mobile Broadband
EMILY	European Mobile Integrated Location System
EPA	Extended Pedestrian A
ERA	Emergency Response to Accidents
ETSI	European Telecommunications Standards Institute
ETU	Extended Typical Urban
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FH	Frequency Hopping
GDOP	Geometric Dilution of Precision
GERAN	GSM/EDGE Radio Access Network
GLONASS	*Globalnaya Navigatsionnaya Sputnikovaya Sistema*
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite Systems
GPRS	General Packet Radio System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTD	Geometric Time Difference
iDEN	Integrated Dispatch Enhanced Network
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Internet Protocol
IPDL	Idle Periods in Downlink
IS	Interim Standard
ISD	Inter-site Distance
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
IVHS	Intelligent Vehicle Highway
LBS	Location-based Services
LCS	Location Services
LIS	Low-interference Subframes
LMU	Location Measurement Unit
LoS	Line-of-sight
LPN	Low Power Node
LPP	LTE Positioning Protocol
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MBS	Metropolitan Beacon Systems
MDT	Minimization of Drive Tests
MIMO	Multiple-input Multiple-output
mMTC	Massive Machine Type Communications
mmWave	Millimetre Wave
MoU	Memorandum of Understanding
MPC	Multipath Components
NB-IoT	Narrowband IoT
NLoS	Non-line-of-sight
NMT	Nordic Mobile Telephone
OFDMA	Orthogonal Frequency-division Multiple Access
OTD	Observed Time Difference
OTDoA	Observed Time Difference of Arrival
PCM	Pilot Correlation Method
PDC	Personal Digital Cellular
PDP	Power-delay Profile
PHS	Personal Handy-phone System
PPP	Precise Point Positioning
ProSe	Proximity-based Services
PRS	Positioning Reference Signal
PSAP	Public Safety Answering Point
PSDCH	Physical Sidelink Discovery Channel
PTP	Precision Time Protocol
PUSCH	Physical Uplink Shared Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Blocks
RFPM	Radio Frequency Pattern Matching
RMSE	Root-mean-square Error

RRH	Remote Radio Head
RSCP	Reference Signal Code Power
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
RSTD	Reference Signal Time Difference
RTD	Real-time Difference
RTT	Round-trip Time
RXLEV	Reception Level
SC-FDMA	Single-carrier Frequency-division Multiple Access
SCH	Synchronization Channel
SHARING	Self-organized Heterogeneous Advanced Radio Networks Generation
SINR	Signal-to-interference-plus-noise Ratio
SLAM	Simultaneous Localization and Mapping
SMG	Special Mobile Group
SMLC	Serving Mobile Location Center
SON	Self-organizing Networks
SPS	Semi-persistent Scheduling
SRS	Sounding Reference Signal
TA	Timing Advance
TACS	Total Access Communications System
TBS	Terrestrial Beacon Systems
TCP	Transport Control Protocol
TDD	Time Division Duplex
TDMA	Time-Division Multiple Access
TDoA	Time Difference of Arrival
TIA	Telecommunications Industry Association
ToA	Time of Arrival
TR	Technical Reports
TS	Technical Specifications
TTFF	Time-to-first-fix
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-reliable and Low Latency Communications
U.S.	United States
UTDoA	Uplink Time Difference of Arrival
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
UWB	Ultra-wideband
VANET	Vehicular Ad-hoc Network
WCDMA	Wideband Code-division Multiple Access
WG	Working Group
WHERE	Wireless Hybrid Enhanced Mobile Radio Estimators
WLAN	Wireless Local Area Networks
WSN	Wireless Sensor Networks.

REFERENCES

[1] "Establishing criteria for the accuracy and reliability of the caller location information in support of emergency services," CEPT Electron. Commun. Committee, Copenhagen, Denmark, Rep. 225, Oct. 2014.

[2] S. Tekinay, "Wireless geolocation systems and services," *IEEE Commun. Mag.*, vol. 36, no. 4, p. 28, Apr. 1998.

[3] A. Dogandzic, J. Riba, G. Seco-Granados, and A. L. Swindlehurst, "Positioning and navigation with applications to communications," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 10–11, Jul. 2005.

[4] G. D. Ott, "Vehicle location in cellular mobile radio systems," *IEEE Trans. Veh. Technol.*, vol. VT-26, no. 1, pp. 43–46, Feb. 1977.

[5] T. S. Rappaport, J. H. Reed, and B. D. Woerner, "Position location using wireless communications on highways of the future," *IEEE Commun. Mag.*, vol. 34, no. 10, pp. 33–41, Oct. 1996.

[6] J. H. Reed, K. J. Krizman, B. D. Woerner, and T. S. Rappaport, "An overview of the challenges and progress in meeting the E-911 requirement for location service," *IEEE Commun. Mag.*, vol. 36, no. 4, pp. 30–37, Apr. 1998.

[7] J. J. Caffery and G. L. Stuber, "Overview of radiolocation in CDMA cellular systems," *IEEE Commun. Mag.*, vol. 36, no. 4, pp. 38–45, Apr. 1998.

[8] C. Drane, M. Macnaughtan, and C. Scott, "Positioning GSM telephones," *IEEE Commun. Mag.*, vol. 36, no. 4, pp. 46–54, Apr. 1998.

[9] J. M. Zagami, S. A. Parl, J. J. Bussgang, and K. D. Melillo, "Providing universal location services using a wireless E911 location network," *IEEE Commun. Mag.*, vol. 36, no. 4, pp. 66–71, Apr. 1998.

[10] S. Tekinay, E. Chao, and R. Richton, "Performance benchmarking for wireless location systems," *IEEE Commun. Mag.*, vol. 36, no. 4, pp. 72–76, Apr. 1998.

[11] M. A. Spirito, "On the accuracy of cellular mobile station location estimation," *IEEE Trans. Veh. Technol.*, vol. 50, no. 3, pp. 674–685, May 2001.

[12] S. S. Soliman and C. E. Wheatley, "Geolocation technologies and applications for third generation wireless," *Wireless Commun. Mobile Comput.*, vol. 2, no. 3, pp. 229–251, 2002.

[13] Y. Zhao, "Standardization of mobile phone positioning for 3G systems," *IEEE Commun. Mag.*, vol. 40, no. 7, pp. 108–116, Jul. 2002.

[14] F. Gustafsson and F. Gunnarsson, "Mobile positioning using wireless networks: Possibilities and fundamental limitations based on available wireless network measurements," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 41–53, Jul. 2005.

[15] A. H. Sayed, A. Tarighat, and N. Khajehnouri, "Network-based wireless location: Challenges faced in developing techniques for accurate wireless location information," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 24–40, Jul. 2005.

[16] G. Sun, J. Chen, W. Guo, and K. J. R. Liu, "Signal processing techniques in network-aided positioning: A survey of state-of-the-art positioning designs," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 12–23, Jul. 2005.

[17] S. Gezici *et al.*, "Localization via ultra-wideband radios: A look at positioning aspects for future sensor networks," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 70–84, Jul. 2005.

[18] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 37, no. 6, pp. 1067–1080, Nov. 2007.

[19] S. Gezici, "A survey on wireless position estimation," *Wireless Pers. Commun.*, vol. 44, no. 3, pp. 263–282, Feb. 2008.

[20] Y. Gu, A. Lo, and I. Niemegeers, "A survey of indoor positioning systems for wireless personal networks," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 13–32, 1st Quart., 2009.

[21] H. Wymeersch, J. Lien, and M. Z. Win, "Cooperative localization in wireless networks," *Proc. IEEE*, vol. 97, no. 2, pp. 427–450, Feb. 2009.

[22] I. Güvenç and C.-C. Chong, "A survey on TOA based wireless localization and NLOS mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 3, pp. 107–124, 3rd Quart., 2009.

[23] J. F. Bull, "Wireless geolocation," *IEEE Veh. Technol. Mag.*, vol. 4, no. 4, pp. 45–53, Dec. 2009.

[24] G. Seco-Granados, J. A. López-Salcedo, D. Jiménez-Baños, and G. López-Risueño, "Challenges in indoor global navigation satellite systems: Unveiling its core features in signal processing," *IEEE Signal Process. Mag.*, vol. 29, no. 2, pp. 108–131, Mar. 2012.

[25] S. S. Cherian and A. N. Rudrapatna, "LTE location technologies and delivery solutions," *Bell Labs Tech. J.*, vol. 18, no. 2, pp. 175–194, Sep. 2013.

[26] D. Dardari, P. Closas, and P. M. Djurić, "Indoor tracking: Theory, methods, and technologies," *IEEE Trans. Veh. Technol.*, vol. 64, no. 4, pp. 1263–1278, Apr. 2015.

[27] Q. D. Vo and P. De, "A survey of fingerprint-based outdoor localization," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 491–506, 1st Quart., 2016.

[28] A. Tahat, G. Kaddoum, S. Yousefi, S. Valaee, and F. Gagnon, "A look at the recent wireless positioning techniques with a focus on algorithms for moving receivers," *IEEE Access*, vol. 4, pp. 6652–6680, 2016.

[29] R. S. Campos, "Evolution of positioning techniques in cellular networks, from 2G to 4G," *Wireless Commun. Mobile Comput.*, vol. 2017, p. 17, Jan. 2017.

[30] Y. Liu, X. Shi, S. He, and Z. Shi, "Prospective positioning architecture and technologies in 5G networks," *IEEE Netw.*, vol. 31, no. 6, pp. 115–121, Nov./Dec. 2017.
[31] T. Farley, "Mobile telephone history," *Telektronikk*, vol. 101, nos. 3–4, pp. 22–34, 2005.
[32] F. Hillebrand, "The creation of standards for global mobile communication: GSM and UMTS standardization from 1982 to 2000," *IEEE Wireless Commun.*, vol. 20, no. 5, pp. 24–33, Oct. 2013.
[33] M. Hata and T. Nagatsu, "Mobile location using signal strength measurements in a cellular system," *IEEE Trans. Veh. Technol.*, vol. VT-29, no. 2, pp. 245–252, May 1980.
[34] "Physical channels and mapping of transport channels onto physical channels (FDD), release 99, V3.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 25.211, Dec. 1999.
[35] "Physical layer procedures (FDD), release 99, V3.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 25.214, Dec. 1999.
[36] *GSM Memorandum of Understanding*, Eur. CEPT, Copenhagen, Denmark, Sep. 1987.
[37] *Cellular System Dual-Mode Mobile Station–Base Station Compatibility Standard*, EIA/TIA Interim Standard IS-54, May 1990.
[38] *Cellular System Recommended Minimum Performance Standards for Full-Rate Speech Codes*, EIA/TIA Interim Standard IS-95, May 1992.
[39] H. Holma and A. Toskala, *WCDMA for UMTS: Radio Access for Third Generation Mobile Communications*. Chichester, U.K.: Wiley, 2000.
[40] T. Halonen, J. Romero, and J. Melero, *GSM, GPRS and EDGE Performance: Evolution Towards 3G/UMTS*. Chichester, U.K.: Wiley, 2004.
[41] "Radio subsystem synchronization, Ph2, V4.0.1," ETSI, Sophia Antipolis, France, Rep. ETSI-SMG GSM TS 05.10, Apr. 1992.
[42] J. Wickman and A. Hakansson, "Localization within GSM," in *Proc. Land Navig. Info. Sys. Conf. Royal Inst. Navig.*, Warwick, U.K., 1990, pp. 1–5.
[43] "Report and order and further notice of proposed rulemaking on revision of the FCC rules to ensure compatibility with enhanced 911 emergency calling systems," Federal Commun. Commission, Washington, DC, USA, Rep. 96-264, 1996.
[44] M. Moeglein and N. Krasner, "An introduction to SnapTrack server-aided GPS technology," in *Proc. ION GPS*, Nashville, TN, USA, Sep. 1998, pp. 333–342.
[45] "Location services (LCS); functional description; stage 2, release 98, V7.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 03.71, Jun. 1999.
[46] "Stage 2 functional specification of user equipment (UE) positioning in UTRAN, release 99, V3.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 25.305, Dec. 1999.
[47] "Location services (LCS); service description; stage 1, release 1999, V3.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 22.071, Oct. 1999.
[48] "IMT-2000 radio interface specifications approved in ITU meeting in Helsinki," ITU, Geneva, Switzerland, ITU/99-22, Nov. 1999.
[49] "UE positioning enhancements, release 4, V1.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 25.847, Dec. 2000.
[50] "Location services (LCS); service description; stage 1, release 4, V4.6.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 22.071, Mar. 2004.
[51] "Stage 2 functional specification of user equipment (UE) positioning in UTRAN, release 7, V7.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 25.305, Jun. 2005.
[52] "Stage 2 functional specification of UE positioning in UTRAN, release 10, V10.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 25.305, Sep. 2010.
[53] "Position determination service standard for dual mode spread spectrum systems, V3.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP2 C.S0022-0, Feb. 2001.
[54] "Physical channels and modulation, release 9, V9.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.211, Mar. 2010.
[55] "BS radio transmission and reception, release 13, V13.2.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.104, Jan. 2016.
[56] "Requirements related to technical performance for IMT-Advanced radio interface(s)," ITU-R, Geneva, Switzerland, ITU-R Rep. M.2134, 2008.
[57] "Requirements for support of radio resource management, release 8, V8.23.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.133, Sep. 2013.
[58] S. Abeta, M. Tanno, and M. Iwamura, "Standardization trends in LTE enhancement," *NTT DOCOMO Tech. J.*, vol. 12, no. 1, pp. 42–44, Jun. 2010.
[59] "Positioning support for LTE," 3GPP, Sophia Antipolis, France, Alcatel-Lucent, Paris, France, AT&T, Dallas, TX, USA, CMCC, Ericsson, Stockholm, Sweden, KDDI, Tokyo, Japan, Nokia Siemens Netw., Nortel Netw., Montreal, QC, Canada, Qualcomm Europe, San Diego, CA, USA, Spirent Telecommun. Syst., U.S. Cellular Corporat., Chicago, IL, USA, and Verizon, New York, NY, USA, Rep. RP-080995, Dec. 2008.
[60] "Support for IMS emergency calls over LTE," 3GPP, Sophia Antipolis, France, Alcatel-Lucent, Paris, France, Verizon Wireless, Basking Ridge, NJ, USA, Nortel, Mississauga, ON, Canada, AT&T, Dallas, TX, USA, Qualcomm, San Diego, CA, USA, Motorola, Chicago, IL, USA, Nokia, Espoo, Finland, Nokia Siemens Netw., Ericsson, Stockholm, Sweden, Samsung, Seoul, South Korea, Rep. RP-081140, Dec. 2008.
[61] "Overview of 3GPP release 9, release 9, V0.2.1," 3GPP, Sophia Antipolis, France, Rep. SP-110313, Apr. 2011.
[62] "Support for emergency services," 3GPP, Sophia Antipolis, France, and Nortel, Mississauga, ON, Canada, Rep. R1-084490, Oct. 2008.
[63] "On OTDOA in LTE," 3GPP, Sophia Antipolis, France, and Qualcomm Europe, San Diego, CA, USA, Rep. R1-090353, Jan. 2009.
[64] "Improving the hearability of LTE positioning service," 3GPP, Sophia Antipolis, France, and Qualcomm Europe, San Diego, CA, USA, Rep. R1-090053, Jan. 2009.
[65] "Performance of DL OTDOA with dedicated LCS-RS," 3GPP, Sophia Antipolis, France, and Alcatel-Lucent, Paris, France, Rep. R1-090768, Feb. 2009.
[66] "On OTDOA method for LTE positioning," 3GPP, Sophia Antipolis, France, and Ericsson, Stockholm, Sweden, Rep. R1-090918, Feb. 2009.
[67] "Way forward on OTDOA positioning," 3GPP, Sophia Antipolis, France, Ericsson, Stockholm, Sweden, Alcatel-Lucent, Paris, France, Huawei, Shenzhen, China, LGE, Motorola, Chicago, IL, USA, Nokia, Espoo, Finland, Nokia Siemens Networks, Nortel, Mississauga, ON, Canada, Qualcomm, San Diego, CA, USA, and Samsung, Seoul, South Korea, Rep. R1-091648, Mar. 2009.
[68] "Further considerations on PRS design for LTE Rel-9," 3GPP, Sophia Antipolis, France, and Huawei, Shenzhen, China, Rep. R1-091789, May 2009.
[69] "Evaluation of PRS-assisted OTDOA-based positioning for LTE," 3GPP, Sophia Antipolis, France, and Motorola, Chicago, IL, USA, Rep. R1-091930, May 2009.
[70] "Analysis of UE subframe timing offset measurement sensitivity to OTDoA performance," 3GPP, Sophia Antipolis, France, and Alcatel-Lucent, Paris, France, Rep. R1-092307 Jun. 2009.
[71] "Location services (LCS); service description; stage 1, release 9, V9.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 22.071, Sep. 2009.
[72] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, "LTE-advanced: Next-generation wireless broadband technology [invited paper]," *IEEE Wireless Commun.*, vol. 17, no. 3, pp. 10–22, Jun. 2010.
[73] "LMU performance specification; network based positioning systems in E-UTRAN, release 11, V11.4.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.111, Oct. 2014.
[74] "Chairman's note on simulation assumptions for UTDOA," NTT DOCOMO, Tokyo, Japan, Rep. 3GPP R1-103410, May 2010.
[75] "LS on summary of UTDOA evaluation in RAN1," 3GPP, Sophia Antipolis, France, Rep. R1-106559, Nov. 2010.
[76] "Way forward for network-based positioning for LTE," 3GPP, Sophia Antipolis, France, Alcatel-Lucent, Paris, France, and AT&T, Dallas, TX, USA, Rep. RP-101298, Dec. 2010.
[77] R. F. K. Kelly, "Joint motion to dismiss the amended complaint of TruePosition," U.S. District Court for the Eastern District of Pennsylvania, Civil action, No. 11-4574, Aug. 2012.
[78] "Inclusion of RF pattern matching as a positioning method in the E-UTRAN," 3GPP, Sophia Antipolis, France, and Polaris Wireless, Mountain View, CA, USA, Rep. RP-101445, Dec. 2010.
[79] "RF pattern matching location method in LTE, release 12, V12.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 36.809, Sep. 2013.
[80] "Physical layer; measurements, release 12, V12.2.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.214, Mar. 2015.
[81] "Stage 2 functional specification of UE positioning in E-UTRAN, release 9, V9.10.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.305, Jan. 2013.
[82] "New SI proposal: Positioning enhancements for E-UTRA," 3GPP, Sophia Antipolis, France, Huawei, Shenzhen, China, and HiSilicon, Shenzhen, China, Rep. RP-130680, Jun. 2013.

[83] "Feasibility of positioning enhancements for E-UTRA, release 13, V13.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 36.855, Jan. 2015.

[84] "Requirements for support of radio resource management, release 9, V9.22.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.133, Dec. 2014.

[85] C. Hoymann *et al.*, "LTE release 14 outlook," *IEEE Wireless Commun.*, vol. 54, no. 6, pp. 44–49, Jun. 2016.

[86] "New SID: Study on indoor positioning enhancements for UTRA and LTE," 3GPP, Sophia Antipolis, France, and NextNav, Sunnyvale, CA, USA, Rep. RP-141003, Jun. 2014.

[87] "Study on indoor positioning enhancements for UTRA and LTE, release 13, V13.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 37.857, Jan. 2016.

[88] "Third further notice of proposed rulemaking on wireless E911 location accuracy requirements," Federal Commun. Commission, Washington, DC, USA, Rep. 14-13, Feb. 2014.

[89] "FCC liaison statement," 3GPP, Sophia Antipolis, France, and Federal Commun. Commission, Washington, DC, USA, Rep. RP-140551, May 2014.

[90] "Study on 3D channel model for LTE, release 12, V12.2.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 36.873, Jun. 2015.

[91] "Views on indoor positioning enhancements SI," 3GPP, Sophia Antipolis, France, and Intel Corporat., Santa Clara, CA, USA, Rep. R1-153185, May 2015.

[92] "Physical layer procedures, release 12, V12.10.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.213, Jun. 2016.

[93] "3GPP system to WLAN interworking; system description, release 12, V12.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 23.234, Sep. 2014.

[94] "Requirements for support of radio resource management, release 13, V13.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.133, Sep. 2015.

[95] "Stage 2 functional specification of UE positioning in E-UTRAN, release 13, V13.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.305, Jan. 2016.

[96] S. Fischer, "Observed time difference of arrival (OTDOA) positioning in 3GPP LTE," Qualcomm Technol., San Diego, CA, USA, White Paper, Jul. 2014.

[97] "Location services (LCS); service description; stage 1, release 14, V14.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 22.071, Sep. 2015.

[98] "Third report and order on E-911 phase II requirements," Federal Commun. Commission, Washington, DC, USA, Rep. 99-245, Sep. 1999.

[99] "Order to stay," Federal Commun. Commission, Washington, DC, USA, Rep. 02-210, Jul. 2002.

[100] "Report and order on wireless E911 location accuracy requirements," Federal Commun. Commission, Washington, DC, USA, Rep. 07-166, Sep. 2007.

[101] "Second report and order on wireless E911 location accuracy requirements," Federal Commun. Commission, Washington, DC, USA, Rep. 10-176, Sep. 2010.

[102] "E9-1-1 location accuracy: Indoor location test bed report," CSRIC III Working Group 3, Mar. 2013.

[103] "TruePosition indoor test report," TechnoCom, Carlsbad, CA, USA, Rep., Jun. 2014.

[104] "Fourth report and order on wireless E911 location accuracy requirements," Federal Commun. Commission, Washington, DC, USA, Rep. 15-9, Jan. 2015.

[105] "The 1999 communications review: Towards a new framework for electronic communications infrastructure and associated services," Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions, Eur. Commission, Brussels, Belgium, Rep., Sep. 1999.

[106] B. Ludden *et al.*, "Report on implementation issues related to access to location information by emergency services (E112) in the European Union," CGALIES, Eur. Commission, Brussels, Belgium, Rep., Feb. 2002.

[107] *Commission Recommendation of 25 July 2003 on the Processing of Caller Location Information in Electronic Communication Networks for the Purpose of Location-Enhanced Emergency Call Services*, document 2657, Eur. Commission, Brussels, Belgium, Jul. 2003.

[108] *Memorandum of Understanding for Realisation of Interoperable in-Vehicle eCall*, eSafety Forum, eCall Driving Group, and Eur. Commission, Brussels, Belgium, May 2004.

[109] I. Martin-Escalona, F. Barceló, and J. Paradells, "Delivery of non-standardized assistance data in E-OTD/GNSS hybrid location systems," in *Proc. IEEE PIMRC*, Lisbon, Portugal, Sep. 2002, pp. 2347–2351.

[110] R. Raulefs and S. Plass, "Combining wireless communications and navigation—The WHERE project," in *Proc. IEEE VTC-Fall*, Calgary, AB, Canada, Sep. 2008, pp. 1–5.

[111] A. Dammann *et al.*, "WHERE2 location aided communications," in *Proc. Eur. Wireless Conf.*, Guildford, U.K., Apr. 2013, pp. 1–8.

[112] *Establishing detailed technical requirements and test procedures for the EC type-approval of motor vehicles with respect to their 112-based eCall in-vehicles systems, of 112-based eCall in-vehicle separate technical units and components and supplementing and amending Regulation (EU) 2015/758 of the European Parliament and of the Council with regard to the applicable standards*, Eur. Commission, Brussels, Belgium, Sep. 2016.

[113] *Global Navigation Satellite System. Emergency Response System in Case of Accidents. Car System Call Emergency Services. General Technical Requirements*, GOST Standard R 54620-2011, Sep. 2012.

[114] V. Gladkikh and A. Klimovskiy, *Technical Regulation in the Scope of ERA-GLONASS Emergency Response System Deployment*, document AECS-03-06, AECS, Moscow, Russia, Feb. 2014.

[115] M. A. Spirito, S. Poykko, and O. Knuuttila, "Experimental performance of methods to estimate the location of legacy handsets in GSM," in *Proc. IEEE VTC-Fall*, Atlantic City, NJ, USA, Aug. 2001, pp. 2716–2720.

[116] D.-B. Lin and R.-T. Juang, "Mobile location estimation based on differences of signal attenuations for GSM systems," *IEEE Trans. Veh. Technol.*, vol. 54, no. 4, pp. 1447–1454, Jul. 2005.

[117] J. Borkowski, J. Niemela, and J. Lempiainen, "Enhanced performance of cell ID+RTT by implementing forced soft handover algorithm," in *Proc. IEEE VTC-Fall*, Los Angeles, CA, USA, Sep. 2004, pp. 3545–3549.

[118] J. Wennervirta and T. Wigren, "RTT positioning field performance," *IEEE Trans. Veh. Technol.*, vol. 59, no. 7, pp. 3656–3661, Sep. 2010.

[119] W. Xu, M. Huang, C. Zhu, and A. Dammann, "Maximum likelihood TOA and OTDOA estimation with first arriving path detection for 3GPP LTE system," *Trans. Emerg. Telecommun. Technol.*, vol. 27, no. 3, pp. 339–356, 2016.

[120] J. A. del Peral-Rosado *et al.*, "Floor detection with indoor vertical positioning in LTE femtocell networks," in *Proc. IEEE Globecom Workshops*, San Diego, CA, USA, Dec. 2015, pp. 1–6.

[121] H. Laitinen, J. Lähteenmäki, and T. Nordström, "Database correlation method for GSM location," in *Proc. IEEE VTC-Spring*, Rhodes, Greece, May 2001, pp. 2504–2508.

[122] A. J. Weiss, "On the accuracy of a cellular location system based on RSS measurements," *IEEE Trans. Veh. Technol.*, vol. 52, no. 6, pp. 1508–1518, Nov. 2003.

[123] T. Wigren, "Fingerprinting localisation using round trip time and timing advance," *IET Commun.*, vol. 6, no. 4, pp. 419–427, Mar. 2012.

[124] "E9-1-1 location accuracy: Report—Leveraging LBS and emerging location technologies for indoor wireless E9-1-1," CSRIC III Working Group 3, Mar. 2013.

[125] A. Varshavsky, E. De Lara, J. Hightower, A. LaMarca, and V. Otsason, "GSM indoor localization," *Pervasive Mobile Comput.*, vol. 3, no. 6, pp. 698–720, Dec. 2007.

[126] J. Borkowski and J. Lempiäinen, "Practical network-based techniques for mobile positioning in UMTS," *EURASIP J. Adv. Signal Process.*, vol. 2006, Aug. 2006, Art. no. 012930.

[127] T. Wigren, "LTE fingerprinting localization with altitude," in *Proc. IEEE VTC-Fall*, Quebec City, QC, Canada, Sep. 2012, pp. 1–5.

[128] Y.-H. Wang, H. Li, X.-L. Luo, Q.-M. Sun, and J.-N. Liu, "A 3D fingerprinting positioning method based on cellular networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 7, p. 8, 2014.

[129] R. M. Vaghefi and R. M. Buehrer, "Cooperative RF pattern matching positioning for LTE cellular systems," in *Proc. IEEE PIMRC*, Washington, DC, USA, Sep. 2014, pp. 264–269.

[130] J. Turkka and T. Ristaniemi, *Localization Architecture for Multi-Layer, Multi-RAT Heterogeneous Network, Deliverable D6.3*, Magister Solutions, Jyväskylä, Finland, Feb. 2015.

[131] Y. Zhao, "Mobile phone location determination and its impact on intelligent transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 1, no. 1, pp. 55–64, Mar. 2000.

[132] S. Fischer, H. Koorapaty, E. Larsson, and A. Kangas, "System performance evaluation of mobile positioning methods," in *Proc. IEEE VTC-Spring*, Houston, TX, USA, May 1999, pp. 1962–1966.

[133] G. Hein, B. Eissfeller, V. Oehler, and J. Winkel, "Synergies between satellite navigation and location services of terrestrial mobile communication," in *Proc. ION GPS*, Salt Lake City, UT, USA, Sep. 2000, pp. 535–544.

[134] C. R. Drane, P. Duffett-Smith, S. Hern, and J. Brice, "Mobile location without network-based synchronization or how to do E-OTD without LMUs," in *Proc. AeroSense*, Orlando, FL, USA, Apr. 2003, pp. 59–66.

[135] R. M. Faragher and P. J. Duffett-Smith, "Measurements of the effects of multipath interference on timing accuracy in a cellular radio positioning system," *IET Radar Sonar Navig.*, vol. 4, pp. 818–824, Dec. 2010.

[136] "Technical options for E9-1-1 location accuracy," CSRIC Working Group 4C, Mar. 2011.

[137] J. Sadowski, "TDOA navigation using CDMA2000 signals—Experimental results," in *Proc. UPINLBS*, Corpus Christi, TX, USA, Nov. 2014, pp. 265–271.

[138] P. J. Duffett-Smith and M. D. Macnaughtan, "Precise UE positioning in UMTS using cumulative virtual blanking," in *Proc. 3rd Int. Conf. 3G Mobile Commun. Technol.*, London, U.K., May 2002, pp. 355–359.

[139] J. Medbo, I. Siomina, A. Kangas, and J. Furuskog, "Propagation channel impact on LTE positioning accuracy: A study based on real measurements of observed time difference of arrival," in *Proc. IEEE PIMRC*, Tokyo, Japan, Sep. 2009, pp. 2213–2217.

[140] C. Gentner *et al.*, "Particle filter based positioning with 3GPP-LTE in indoor environments," in *Proc. IEEE/ION PLANS*, Myrtle Beach, SC, USA, Apr. 2012, pp. 301–308.

[141] C. Mensing, S. Sand, and A. Dammann, "Hybrid data fusion and tracking for positioning with GNSS and 3GPP-LTE," *Int. J. Navig. Observation*, vol. 2010, pp. 1–12, Jun. 2010.

[142] C. Mensing, "Location determination in OFDM based mobile radio systems," Ph.D. dissertation, Faculty Elect. Eng. Inf. Technol., Technische Universität München, Munich, Germany, 2013.

[143] C. Mensing, S. Sand, A. Dammann, and W. Utschick, "Interference-aware location estimation in cellular OFDM communications systems," in *Proc. IEEE ICC*, Dresden, Germany, Jun. 2009, pp. 1–6.

[144] J. A. del Peral-Rosado, J. A. López-Salcedo, F. Zanier, and M. Crisci, "Achievable localization accuracy of the positioning reference signal of 3GPP LTE," in *Proc. ICL-GNSS*, Starnberg, Germany, Jun. 2012, pp. 1–6.

[145] J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, and M. Crisci, "Analysis of positioning capabilities of 3GPP LTE," in *Proc. ION GNSS*, Nashville, TN, USA, Sep. 2012, pp. 650–659.

[146] J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, and M. Crisci, "Joint maximum likelihood time-delay estimation for LTE positioning in multipath channels," *EURASIP J. Adv. Signal Process.*, vol. 2014, no. 1, pp. 1–13, 2014.

[147] M. Driusso, F. Babich, F. Knutti, M. Sabathy, and C. Marshall, "Estimation and tracking of LTE signals time of arrival in a mobile multipath environment," in *Proc. ISPA*, Zagreb, Croatia, Sep. 2015, pp. 276–281.

[148] R. M. Vaghefi and R. M. Buehrer, "Improving positioning in LTE through collaboration," in *Proc. IEEE WPNC*, Dresden, Germany, Mar. 2014, pp. 1–6.

[149] Z. Bo, D. Yuanfeng, and Y. Dongkai, "The impact of new features on positioning technology in LTE-A system," *Mobile Inf. Syst.*, vol. 2015, p. 10, Feb. 2015.

[150] P.-H. Tseng and K.-T. Lee, "A femto-aided location tracking algorithm in LTE-A heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 748–762, Jan. 2017.

[151] C.-Y. Chen and W. R. Wu, "Three-dimensional positioning for LTE systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3220–3234, Apr. 2017.

[152] M. Driusso *et al.*, "Vehicular position tracking using LTE signals," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3376–3391, Apr. 2017.

[153] M. Driusso *et al.*, "Indoor positioning using LTE signals," in *Proc. IPIN*, Alcalá de Henares, Spain, Oct. 2016, pp. 1–8.

[154] Z. Z. M. Kassas, J. Khalife, K. Shamaei, and J. Morales, "I hear, therefore I know where I am: Compensating for GNSS limitations with cellular signals," *IEEE Signal Process. Mag.*, vol. 34, no. 5, pp. 111–124, Sep. 2017.

[155] F. Van Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS*. Boston, MA, USA: Artech House, 2009.

[156] P. J. Duffett-Smith and J. Craig, "Matrix, and enhanced satellite positioning," in *Proc. 5th Int. Conf. 3G Mobile Commun. Technol.*, London, U.K., Oct. 2004, pp. 364–367.

[157] P. J. Duffett-Smith and B. Tarlow, "E-GPS: Indoor mobile phone positioning on GSM and W-CDMA," in *Proc. ION GNSS*, Long Beach, CA, USA, Sep. 2005, pp. 2762–2768.

[158] C. Gioia and D. Borio, "Stand-alone and hybrid positioning using asynchronous pseudolites," *Sensors*, vol. 15, no. 1, pp. 166–193, 2015.

[159] B. Li, B. Harvey, and T. Gallagher, "Using barometers to determine the height for indoor positioning," in *Proc. IPIN*, Montbéliard, France, Oct. 2013.

[160] H. Xia, X. Wang, Y. Qiao, J. Jian, and Y. Chang, "Using multiple barometers to detect the floor location of smart phones with built-in barometric sensors for indoor positioning," *Sensors*, vol. 15, no. 4, pp. 7857–7877, Mar. 2015.

[161] M. Romanovas *et al.*, "A study on indoor pedestrian localization algorithms with foot-mounted sensors," in *Proc. IPIN*, Sydney, NSW, Australia, Nov. 2012, pp. 1–10.

[162] W. Song, J. W. Lee, B. S. Lee, and H. Schulzrinne, "Finding 9-1-1 callers in tall buildings," in *Proc. IEEE WoWMoM*, Sydney, NSW, Australia, Jun. 2014, pp. 1–9.

[163] C. Fritsche and A. Klein, "Nonlinear filtering for hybrid GPS/GSM mobile terminal tracking," *Int. J. Navig. Observation*, vol. 2010, Jun. 2010, Art. no. 149065.

[164] F. Barcelo-Arroyo, I. Martin-Escalona, and C. Manente, "A field study on the fusion of terrestrial and satellite location methods in urban cellular networks," *Eur. Trans. Telecommun.*, vol. 21, no. 7, pp. 632–639, 2010.

[165] G. D. Angelis, G. Baruffa, and S. Cacopardi, "GNSS/cellular hybrid positioning system for mobile users in urban scenarios," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 313–321, Mar. 2013.

[166] S. Tao, V. Manolopoulos, S. Rodriguez, M. Ismail, and A. Rusu, "Hybrid vehicle positioning and tracking using mobile phones," in *Proc. Int. Conf. ITS Telecommun.*, St. Petersburg, Russia, Aug. 2011, pp. 315–320.

[167] J. A. del Peral-Rosado *et al.*, "Performance analysis of hybrid GNSS and LTE localization in urban scenarios," in *Proc. NAVITEC*, Noordwijk, The Netherlands, Dec. 2016, pp. 1–8.

[168] P. Mirowski, T. K. Ho, S. Yi, and M. MacDonald, "SignalSLAM: Simultaneous localization and mapping with mixed WiFi, Bluetooth, LTE and magnetic signals," in *Proc. IPIN*, Montbéliard, France, Oct. 2013, pp. 1–10.

[169] R. Faragher and R. Harle, "SmartSLAM–an efficient smartphone indoor positioning system exploiting machine learning and opportunistic sensing," in *Proc. ION GNSS*, Nashville, TN, USA, Sep. 2013, pp. 1–14.

[170] D. Bladsjö, M. Hogan, and S. Ruffini, "Synchronization aspects in LTE small cells," *IEEE Commun. Mag.*, vol. 51, no. 9, pp. 70–77, Sep. 2013.

[171] H. Li, L. Han, R. Duan, and G. M. Garner, "Analysis of the synchronization requirements of 5G and corresponding solutions," *IEEE Commun. Stand. Mag.*, vol. 1, no. 1, pp. 52–58, Mar. 2017.

[172] M. Weiss *et al.*, "Time-aware applications, computers, and communication systems (TAACCS)," NIST, Gaithersburg, MD, USA, Rep. 1867, Feb. 2015, doi: 10.6028/NIST.TN.1867.

[173] G. Ding, Z. Tan, J. Wu, and J. Zhang, "Efficient indoor fingerprinting localization technique using regional propagation model," *IEICE Trans. Commun.*, vol. E97-B, no. 8, pp. 1728–1741, Aug. 2014.

[174] G. Ding, Z. Tan, J. Wu, J. Zeng, and L. Zhang, "Indoor fingerprinting localization and tracking system using particle swarm optimization and kalman filter," *IEICE Trans. Commun.*, vol. E98-B, no. 3, pp. 502–514, Mar. 2015.

[175] "Study on LTE device to device proximity services; radio aspects, release 12, V12.0.1," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 36.843, Mar. 2014.

[176] "Stage 2 functional specification of UE positioning in E-UTRAN, release 11, V11.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.305, Jun. 2012.

[177] "Requirements for support of A-GPS (FDD), release 6," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 25.171, May 2004.

[178] "Requirements for support of A-GNSS, release 9, V9.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 36.171, Mar. 2010.

[179] "Stage 2 functional specification of UE positioning in E-UTRAN, release 14, V14.0.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TS 36.305, Dec. 2016.

[180] *Recommended Minimum Performance Specification for C.S0022-0 Spread Spectrum Mobile Stations V1.0*, 3GPP Standard 3GPP2 C.S0036-0, Mar. 2002.

[181] "IMT vision—Framework and overall objectives of the future development of IMT for 2020 and beyond," ITU, Geneva, Switzerland, Rep. ITU-R M.2083-0, Sep. 2015.

[182] "5G automotive vision," 5G-PPP, Eur. Commission, ERTICO ITS Europe, Brussels, Belgium, White Paper, Oct. 2015.

[183] H2020 Programme (2016). *HIGHTS Project: High Precision Positioning for Cooperative-ITS*. [Online]. Available: http://www.hights.eu.

[184] "5G white paper, final executive version," NGMN Alliance, Frankfurt, Germany, Feb. 2015.

[185] "Feasibility study on new services and markets technology enablers; stage 1, release 14, V14.1.0," 3GPP, Sophia Antipolis, France, Rep. 3GPP TR 22.891, Jun. 2016.

[186] H. Wymeersch, G. Seco-Granados, G. Destino, D. Dardari, and F. Tufvesson, "5G mmWave positioning for vehicular networks," vol. 24, no. 6, pp. 80–86, Dec. 2017.

[187] R. Di Taranto *et al.*, "Location-aware communications for 5G networks: How location information can improve scalability, latency, and robustness of 5G," *IEEE Signal Process. Mag.*, vol. 31, no. 6, pp. 102–112, Nov. 2014.

[188] J. A. del Peral-Rosado, J. López-Salcedo, S. Kim, and G. Seco-Granados, "Feasibility study of 5G-based localization for assisted driving," in *Proc. ICL GNSS*, Barcelona, Spain, Jun. 2016, pp. 1–6.

[189] A. Dammann, T. Jost, R. Raulefs, M. Walter, and S. Zhang, "Optimizing waveforms for positioning in 5G," in *Proc. SPAWC*, Edinburgh, U.K., Jul. 2016, pp. 1–5.

[190] A. Guerra, F. Guidi, and D. Dardari, "Position and orientation error bound for wideband massive antenna arrays," in *Proc. IEEE ICC Workshops*, London, U.K., Jun. 2015, pp. 853–858.

[191] A. Shahmansoori, G. E. Garcia, G. Destino, G. Seco-Granados, and H. Wymeersch, "5G position and orientation estimation through millimeter wave MIMO," in *Proc. IEEE Globecom Workshops*, San Diego, CA, USA, Dec. 2015, pp. 1–6.

[192] V. Savic and E. G. Larsson, "Fingerprinting-based positioning in distributed massive MIMO systems," in *Proc. VTC Fall*, Boston, MA, USA, Sep. 2015, pp. 1–5.

[193] W. Wang, T. Jost, C. Gentner, S. Zhang, and A. Dammann, "A semiblind tracking algorithm for joint communication and ranging with OFDM signals," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5237–5250, Jul. 2016.

[194] K. Witrisal, S. Hinteregger, J. Kulmer, E. Leitinger, and P. Meissner, "High-accuracy positioning for indoor applications: RFID, UWB, 5G, and beyond," in *Proc. IEEE Int. Conf. RFID*, Orlando, FL, USA, May 2016, pp. 1–7.

[195] K. Witrisal *et al.*, "High-accuracy localization for assisted living: 5G systems will turn multipath channels from foe to friend," *IEEE Signal Process. Mag.*, vol. 33, no. 2, pp. 59–70, Mar. 2016.

[196] C. Gentner *et al.*, "Multipath assisted positioning with simultaneous localization and mapping," *IEEE Trans. Wireless Commun.*, vol. 15, no. 9, pp. 6104–6117, Sep. 2016.

[197] R. Raulefs, S. Zhang, and C. Mensing, "Bound-based spectrum allocation for cooperative positioning," *Trans. Emerg. Telecommun. Technol.*, vol. 24, no. 1, pp. 69–83, 2013.

[198] A. Dammann, R. Raulefs, and S. Zhang, "On prospects of positioning in 5G," in *Proc. IEEE ICC Workshops*, London, U.K., Jun. 2015, pp. 1207–1213.

[199] M. Koivisto *et al.*, "Joint device positioning and clock synchronization in 5G ultra-dense networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 2866–2881, May 2017.

[200] M. Koivisto *et al.*, "High-efficiency device positioning and location-aware communications in dense 5G networks," *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 188–195, Jul. 2017.

[201] Q. Han, S. Liang, and H. Zhang, "Mobile cloud sensing, big data, and 5G networks make an intelligent and smart world," *IEEE Netw.*, vol. 29, no. 2, pp. 40–45, Mar./Apr. 2015.

[202] J. Choi *et al.*, "Millimeter-wave vehicular communication to support massive automotive sensing," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 160–167, Dec. 2016.

[203] V. Lucas-Sabola, G. Seco-Granados, J. A. López-Salcedo, J. A. García-Molina, and M. Crisci, "Cloud GNSS receivers: New advanced applications made possible," in *Proc. ICL GNSS*, Barcelona, Spain, Jun. 2016, pp. 1–6.

[204] A. Brown and R. Silva, "TIDGET mayday system for motorists," in *Proc. IEEE PLANS*, Las Vegas, NV, USA, Apr. 1994, pp. 480–486.

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