18th International Conference on Information Fusion
Washington, DC - July 6-9, 2015

New Trends in Radio Network Positioning

Kamiar Radnosrati, Fredrik Gunnarsson†, Fredrik Gustafsson
Department of Electrical Engineering, Linköping University, Linköping, Sweden
Email: kamiar.radnosrati@liu.se, fredrik@isy.liu.se
† Ericsson Research, Linköping, Sweden, Email: fredrik.gunnarsson@ericsson.com

***Abstract*—Positioning in radio networks is a well established research area. The dominating approach has been that positioning algorithms are implemented in the higher levels of the communication system based on position related information derived in the lowest (physical) layer. Examples of measurement include received signal strength (RSS), time of arrival (TOA), angle of arrival (AOA), and fusion and filtering is a straightforward task. The technical driver for positioning has been E911 and for commercially driver comes from location based services and logistics management. These demands are fundamental in the development of positioning in future radio networks standards. There is today a trend for accuracy demand that goes beyond what can be achieved with todays measurements. Another trend is that measurements and positioning algorithms are approaching each other, so some parts of the positioning are performed on the chip-sets (lowest layer) and low-level measurements are available to the operating system (highest level). The purpose of this survey is to describe this trend in more detail, with examples of developments in cellular networks as well as WiFi and Bluetooth.**

I. Introduction

Awareness of the position of a device, either in absolute terms or relative to a reference location, is becoming increasingly important. Use cases include emergency calls positioning, navigation, gaming, autonomic vessels, logistics, fleet management, proximity services, location-based services, network management to mention a few. Up to date, it has mainly been emergency call positioning that has driven much of the work in cellular networks due to regulatory requirements. However, some use cases can also be addressed via crude positioning such as cell ID association.

The emergency call positioning requirements by the Federal Communications Commission (FCC) in the United States have been refined several times, initially with requirements on network-based positioning, and subsequently with tighter requirements on mobile-assisted positioning [1], [2]. Recently [3], FCC has yet again refined the requirements to give particular attention to requirements for positioning of indoor devices. These requirements are presented as a roadmap with stricter requirements over time, and considering all mobiles, both outdoors and indoors. The requirement is a horizontal accuracy corresponding to a dispatchable address or within a radius of 50 meters for 40 percent of all wireless 911 calls within two years, gradually tightened to 80 percent of the wireless 911 calls within six years. Furthermore, for vertical positioning information, compatible mobiles shall deliver barometric pressure information within three years. In addition, operators commit to develop a specific vertical location accuracy metric that would be used as the standard for any future deployment, and to be generally adopted within eight years. An alternative, or a complement to pressure reports, is a plausible nationwide National Emergency Address Database (NEAD) containing locations of WiFi access points and Bluetooth beacons.

Wireless network positioning is based on measurements gathered either at the base stations, at the mobile stations and reported to the network, or a combination. It may be based on snapshot measurements or time series of measurements. The survey articles [2], [4]–[8] provide further information about positioning in wireless networks and associated standardization. This paper aims at extending the measurement survey in [8] to include recent advances in standardization and technology.

The outline of the paper is as follows. Section II presents a general sensor fusion framework for positioning based on generic measurements, and Section III describes available measurements for positioning in wireless networks, separated in different key categories and associated with accuracy statistics. Moreover, Section IV addresses some positioning aspects in considerations of the presented framework, models and measurements, followed by some conclusions in Section V.

II. Positioning Framework and System Model

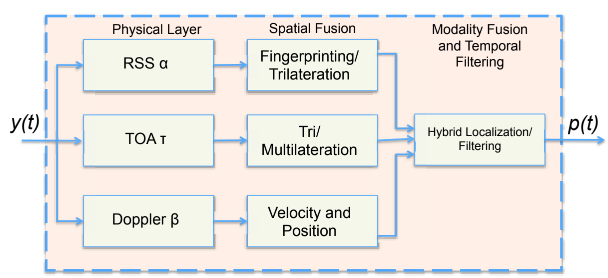

Fig. 1: Different layers of fusion for positioning in radio networks.

Figure 1 provides an overview of the information flow in positioning algorithms as they appear in literature today. This section will summarize the different levels of fusion in terms of signal models.

The underlying notation is as follows. Denote the three-dimensional mobile position at time t by $p_t = (X_t, Y_t, Z_t)^T$, and the known reference point (base station) positions by

$p^i = (X^i, Y^i, Z^i)^T$. The reference points can in general move in time, as is the case in some ad-hoc networks and sensor networks problems. A generic measurement y_t^i relative to reference point i is a function $h_{type}(p_t, p_t^i)$ of both mobile position and reference position position, and it is subject to an uncertainty e_t^i. Hence

$$y_t^i = h_{type}(p_t, p_t^i) + e_t^i \tag{1}$$

A. Level 1: Radio Measurements

On the physical layer, a pilot symbol $s_i(t)$ is transmitted, and the receiver samples the signal

$$z_i(t) = \sum_{k=0}^{n} \alpha_{ik} s\big(\beta_{ik}(t - \tau_{ik}\big) + e_{ik}(t). \tag{2}$$

Here, we have introduced

- The impulse response α_{ik} of the (multi-path) channel.
- The time delay per incoming path τ_{ik}. In case of pure line-of-sight, this is equal to $|p - p^i|/c$, where c is the speed of light.
- The Doppler shift β_{ik}, which scales time.

Suppose that these parameters can be estimated accurately in the receiver. Then, we can define the following position related measurements:

- TOA (time of arrival) corresponds to τ_{ik}, which yields the high-level measurement
  $$y_t^{i,\text{TOA}} = \|p_t - p_t^i\| + e_t^{i,\text{TOA}} \tag{3}$$
  where the error $e_t^{i,\text{TOA}}$ captures both the estimation error and the model error due to multipath. The LTE positioning evaluation in [9] presents a Gaussian estimation error of variance 8.5 meters based on simulations with a realistic receiver.
- If there are several synchronized transmitters and the receiver in un-synchronized, we get a TDOA (time difference of arrival measurement) by computing pair-wise differences of τ, yielding
  $$y_t^{ij,\text{TDOA}} = \|p_t - p^i\| - \|p_t - p^j\| + e_t^{i,\text{TOA}} - e_t^{j,\text{TOA}} \tag{4}$$
- Round trip time (RTT) measurements are basically the sum of two TOA measurements in uplink and downlink, respectively,
  $$y_t^{i,\text{TOA}} = 2\|p_t - p^i\| + e_t^{i,\text{TOA,uplink}} + e_t^{i,\text{TOA,downlink}}. \tag{5}$$
- AOA (angle of arrival) can be computed to comparing different delays τ to multiple antennas in the receiver, and the high-level measurement is
  $$y_t^{i,\text{AOA}} = \arctan(X_t - X^i, Y_t - Y^i) + e_t^{i,\text{AOA}} \tag{6}$$
  For two nearby receivers, separated in distance D meters (less than half a wavelength), we can use the simple formula $y_t^{i,\text{AOA}} = \arccos(c\tau/D)$. There is a rich literature on array processing with much more sophisticated algorithms, see [10].

  Another more coarse method to estimate AOA is based on the antenna lobe diagram, that usually provides a sector of width between 60 and 180 degrees. This can be refined [11] based on non-coherent power measurements of multiple sectors at the same site to about 10-20 degrees in the sector overlap regions.
- RSS (received signal strength) is basically the total energy $\sum_{k=0}^{n} \alpha_{ik}^2$. The log-distance model states that
  $$y_t^{i,\text{RSS}} = P - b \log\big(\|p_t - p^i\|\big) + e_t^{i,\text{RSS}}. \tag{7}$$
  Here, P is the transmitted power (which might be known) and b is the path loss exponent (usually between 2 and 3).
- The Doppler parameter β provides a measurement of the relative speed
  $$y_t^{i,\text{Doppler}} = \frac{d\|p_t - p^i\|}{dt} + e_t^{i,\text{Doppler}}. \tag{8}$$

B. Level 2: Spatial Fusion

Given N transmitters, we have a set of equations

$$y_t^{i,\text{type}} = h^{\text{type}}\big(\|p_t - p^i\|\big) + e_t^{i,\text{type}}, \quad i = 1, \ldots, N. \tag{9}$$

where type is either TOA, TDOA, AOA, RSS or Doppler. Given a sufficient large N, this forms a system of equations which under quite general conditions has a unique solution in p_t. There is a vast literature describing the principles of trilateration (TOA), multilateration (TDOA), triangulation (AOA), trilateration or fingerprinting (RSS), and multi-static radar (Doppler).

C. Level 3: Modality Fusion and Temporal Filtering

Using measurements of different modality (kind) is not a problem and is covered in the same nonlinear set of equation framework as (9). The only difference is that we list all types available.

Here, also other sensor information can be entered. One complementary sensor that resolves the tricky vertical position problems is barometric pressure, that provides

$$y_t^{i,\text{baro}} = \|Z_t - Z^i\| + e_t^{i,\text{baro}}. \tag{10}$$

The inertial sensor unit in smart phones is today used to compute a lot of motion related parameters, for instance the motion state (still, walking, running, vehicle, etc.) and step detections. These can be used on the device for positioning, but also transmitted to the network.

Further, it is common knowledge how to add a motion model of the kind

$$x_{t+1} = f(x_t, v_t). \tag{11}$$

A nonlinear filter gives a smooth interpolation of the position estimates, and can also be used to predict future positions.

III. IMPROVED MEASUREMENTS

This section continues the brief overview of radio network measurements in Section II, and provides a practical survey similar to [8], but extended with recent measurements and standards. Lower layer techniques for providing these measurements are not addressed, and instead we refer to [5], [12] for 2G, [2], [13] for 3G and, [14], [15] for 4G/WiFi respectively, while [16] provides an overview of error sources in general systems.

Table I provides typical accuracy levels of position measurements covering various wireless systems. First, the timing measurements are based on synchronization techniques. Additionally, it is assumed that measurements are performed in LOS conditions. LTE-related values are provided from the best case scenario, i.e. highest frequency in timing measurements, to worst case conditions. Moreover, in most of the measurements, PRS pilot signal of the LTE system, which mainly gives the best performance compared to other pilot signals, is investigated.

A. Received signal strength

Consider the RSS measurement (7). The reference (transmission) power is assumed either to be known or broadcasted through the network. Having the transmitted and received powers known to the system, the channel attenuation can be computed. In addition to the measurement noise introduced in 7, one might also consider the diffraction factor. This way, 7 can be re-written as:

$$y_t^{i,\mathrm{RSS}} = P - b\log\left(\|p_t - p^i\|\right) + e_t^{i,\mathrm{RSS}} + d_t^{i,\mathrm{RSS}}. \quad (12)$$

where d_t^i is the diffraction. The typical measurement noise (e_t) is on the order of 3 dB in standard deviation. Propagation also features diffraction effects which resembles as shadow fading that is a lowpass spatial process. A number of methods exists to deal with the diffraction error. One way is to lump it together with the measurement error. This way, $std(e_t + d_t) \approx$ 6-10 dB. Another approach is to capture these variations in a model/database which essentially forms the fingerprinting method. A third way is to assume that the shadow fading is only present in the intermediate to far field from antenna, but not in the near field. This way, in the near field, the only source of error is the measurement noise.

The approach introduced below is based on the inherit feature of diffraction. That is, by taking advantage of the high temporal correlation feature of diffraction, one can introduce the difference equation as below resulting in d_t to be discarded.

$$\begin{aligned} y_t^{i,\mathrm{RSS}} - y_{t-1}^{i,\mathrm{RSS}} = &- b\log\left(\|p_t - p^i\|\right) + b\log\left(\|p_{t-1} - p^i\|\right) \\ &+ e_t^{i,\mathrm{RSS}} - e_{t-1}^{i,\mathrm{RSS}} \end{aligned} \quad (13)$$

In addition to RSS-based channel attenuation computation, It is also possible to utilize a predicted or measured spatial digital map with RSS values.

B. Time of arrival and round-trip time

Handshake procedures generate RTT/ToF/range measurements according to (5). [11] provides a novel method for RTT calculations in LTE systems on the uplink timing alignment mechanism.

Performance analysis performed by [17], introduce different levels of accuracies based on the pilot symbols used by the LTE system and also the frequency. The best estimation can be achieved in the 20 MHz system, as expected, while PRS pilot signal is used. In this scenario, the σ_{CRLB} of measurement lies between 0.1 ns to 10 relating to various SNR values, i.e. $-20 \leq E_s/\sigma^2[dB] \geq 20$. Keeping the pilot signal as PRS but changing the system frequency to 1.4 MHz results in a σ_{CRLB} approximately between 1 ns to 100 ns in the same range of SNR.

In GSM, as another example, a 26 bit known training sequence in each burst is found by correlation in timing measurements. The bit duration is about 554 m, but using continuous time techniques, time synchronization down to a fraction (say 100 m) is possible. Similar figures hold for the 3G standard universal mobile telecommunications system (UMTS), where the travel time is estimated using the first detected ray in the RAKE algorithm from the known pilot symbols.

C. Barometric Pressure

Lack of accuracy and reliability on top of limited availability to outdoor environments of GPS-based elevation estimation, is the main motivation behind this method. An example of a possible use of a barometer sensor in vertically oriented activities is presented in [18]. Generic measurement of altitude via a pressure sensor relative a known pressure information at a reference altitude provides the altitude measurement (10).

Sources of error in this method are horizontal and vertical distances to the reference point(s) and the time gap. Three sorts of reference points exist. Meteorological stations for weather forecast already deployed by the national meteorological agencies. These stations have coarse spatial density on the amplitude of tens of kilometers and low update frequency of almost once an hour. The elevation of a person with a smart phone in outdoor environment gotten from Digital Elevation Model (DEM)-map based on his current location is called a "DEM reference". The third reference point is based on an ad-hoc fashion of smart phones within the system.

In case a reference pressure is not available, [19] presents a framework that does not depend on any special infrastructure and provides accurate elevation measurements using only smart phones.

It is considered that three sources of errors introduced above, follow $N(0, \sigma_{hs}^2)$, $N(0, \sigma_{vs}^2)$, and $N(0, \sigma_t^2)$ respectively. The final Accuracy obtained applying the system presented in [19] is less than 5 meters in %90 of the cases and less than 3 meters in % 75 of times.

TABLE I: measurements

MEASUREMENT	NOTATION	Accuracy
RSS	$y_t^i = h_{RSS}(\|p_t - p^i\|) + e_t^i$	4-12 dB
TOA	$y_t^i = \|p_t - p^i\| + e_t^i = h_{range}(p_t, p^i) + e_t^i$	1.5-100 M
Barometric Pressure	$y_t^i = \|P(p_t - p^i)\| + e_t^i = h_{bp}(p_t - p^i) + e_t^i$	1 M
TDOA	$y_t^{i,j} = \|p_t - p^i\| - \|p_t - p^j\| + e_t^i - e_t^i = h_{TDOA}(p_t, p^i, p^j) + e_t^i - e_t^i$	1-60 M
AOA	$y_t^i = h_{AOA}(p_t, p^i) + e_t^i$	$1°$-$20°$
RF Fingerprinting	$y_t = h_{MAP}(p_t, p^i) + e_t$	(RSS MAP, 3 dB)
Position Estimation	$y_t = p_t + e_t$	4-20 M

D. Time difference of arrival

Taking time differences of TOA as in (4) provides TDOA measurements that eliminates the clock bias nuisance parameter. It is a practical mobile measurement related to relative distance. The measurements are reported to the network, which performs necessary computations and it is not necessary to communicate the network synchronization nor the reference point locations to the mobile. As for TOA, the synchronization accuracy determines the performance, but also the base station locations. The observed TDOA accuracy requirement for location purposes in WCDMA is 0.5 chip [2] which means an error of about 40 m ($\sigma_e \approx 20$m). Similarly, a TDOA accuracy requirement of 0.5 chip in cdma2000 (advanced forward link trilateration - A-FLT) means 120 m ($\sigma_e \approx 60$m) due to the lower chip rate. On the other hand, satellite navigation systems have a much higher chip rate, so for instance assisted GPS can provide TDOA measurements with $\sigma_e \approx 1$m.

In case of LTE, [17] presents an accuracy of 3.4 ns (corresponds to 1 m) for 20 MHz system at the confidence level %68. In a LTE system running at 1.4 MHz that is apparently a critical scenario for the LTE positioning, when all available pilots (PRS, CRS, PSS and SSS) are used, an accuracy of 72 ns is achieved.

E. Angle of arrival

The use of directional sensitive antennas provide angle of arrival (AOA) information as in. It is today mainly available as a very crude sector information (*e.g* 120^o for a three sector antenna as illustrated in Figure 2). With the use of group antennas this will be improved to about 30^o beam width ($\sigma_e \approx 8$ degrees), and perhaps even better. Geometrically, the spatial resolution of the intersection of two perfectly complementing AOA measurements is limited to $2D\sin(\alpha/2)$, where α is the angular resolution and D the distance between the antennas. For $\alpha = 30^o$, this means 36% of D.

In LTE systems, MIMO pre-coder index is fed back to provide a better performance in AOA-based localization. Reference [20] presents the dispersion rms values for two different environments. 1-5°of AOA rms in rural positions, which gets worse in microcells with rms values of 5-20°

Reference [12] e.g. reports angular dispersion rms values of 1–5 degrees in rural environments and 5–20 degrees in microcells. These figures are roughly of the same size as those presented in example 1. Detailed performance comparisons can be obtained e.g. by using the Cramer-Rao lower bound of [4].

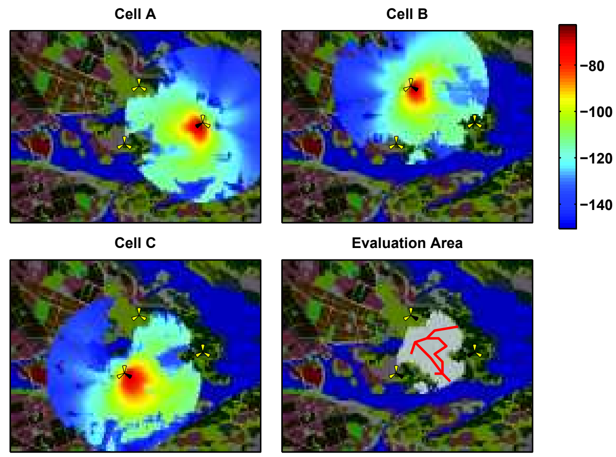

Fig. 2: Use of Directional Sensitive Antennas in AOA

F. RF Fingerprinting

Fingerprinting describes a class of algorithms that removes deterministic components from measurements but using a digital map of these created off-line.

Such a digital map contains for instance RSS measurements relative the reference points either predicted or provided via dedicated measurement scans in the service area. The former is conducted in the network deployment phase using graphical information systems dedicated for network planning

G. Position estimates

A direct position estimate may be available, from instance from GPS. Typical accuracy without differential support is in the order of 5–10 m. According to [21] lowest bandwidth of LTE, i.e. 1 MHz results in 12 meters of position errors in 67% of the time. This improves to 4 meters in case of 18 MHz signal bandwidth of LTE.

IV. Trends

Section II described the area of positioning in radio networks as a more or less closed research area, where only incremental contributions have been seen lately. However, there are some important trends that will change this picture.

A. Trend 1: Tighter Information Exchange

One trend that information and algorithms are shared between different layers in the classical OSI model of a communication system opens up for leaps in development. To motivate with some low hanging fruits, consider the power delay profile (PDP) in Figure 3. PDP can be seen as the estimated squared impulse response α_{ik}^2 for $\tau = 0$. That is, the receiver starts to look for the transmitted symbol when it is known it is transmitted, and the correlation at each time is computed. The true $c\tau$ is indicated by the red line, but how should this be estimated from the PDP? The alternatives include thresholding with a fixed or relative threshold, first peak, strongest peak and so on. Further, RSS is the integral over a vertical slice. From the figure, we can conclude the following:

- There are segments in the test where there is non line of sight (NLOS) condition.
- There are many multi-path components.
- There is a strong spatial correlation in that nearby PDP's look quite similar.

All these effects give rise to ambiguities in the estimated RSS and TOA. However, the PDP contains useful information about the quality (variance of $e_t^{i,\text{type}}$), the temporal correlation between $e_t^{i,\text{type}}$ and $e_{t-1}^{i,\text{type}}$ and the modularity correlation between $e_t^{i,\text{TOA}}$ and $e_t^{i,\text{RSS}}$. If the PDP was available in the higher levels, more sophisticated algorithms taking these facts into account could easily be derived.

The bottom line of this motivation is that the whole chain of information should be considered, not being restricted of the classical OSI layers.

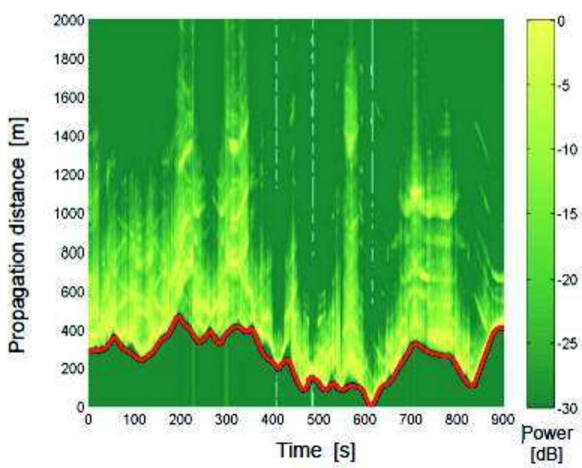

Fig. 3: Example of power delay profile (PDP) from an LTE deployment as a function of time. Red line indicates the true distance $\|p_t - p^i\|$ according to a position reference system.

B. Trend 2: New and Better Information

1) New timing measurements: Two algorithms are introduced below.

Timing Measurements: IEEE 802.11v implements timing measurements as an optional management for STAtions(STA). Those STAs who do not support this procedure, shall ignore a received timing measurement frame. Reference [22] presents the work flow of various Wireless Network Management(WNM) procedures of IEEE 802.11v standard including timing measurements that is also presented in Figure 4.

Initiation or stopping an ongoing procedure takes place by a "Request frame" sent by STA. The value of the trigger field dictates if it's an initiative frame or a stop one. IEEE Std 802.1AS defines a protocol for clock synchronizations between STAs. Timing Measurement action frames then will be sent by a sending STA. With the first action frame, both sides capture timestamps. Transmission time of he action frame (t1) and arrival time of ACK response (t4) is stored by the sending side. Meanwhile, receiving STA captures action frame arrival time (t2) and the ACK response sent time (t3). The sending STA then transfers its captured timestamps (t1 and t4) to the other STA.

Assuming the wireless channel to be symmetric, the offset of the clock at the receiving STA relative to the sending STA is given by the relative timing offset $[(t2t1)(t4t3)]/2$.

Fine Timing Measurements: This feature is supposed to be officially published by late 2015. However, the revision [23] is publicly available. More over, The proposal [24] that discusses new features for an enhanced indoor positioning, consider various candidates in this regard. In this proposal, it is mentioned that UEs should report FTM also to the radio network in order to enable accurate range estimations. Although it is nearly the same as its predecessor timing measurement, some enhancements are expected. Timestamp resolution increment from 10 ns to 100 ps is one example.

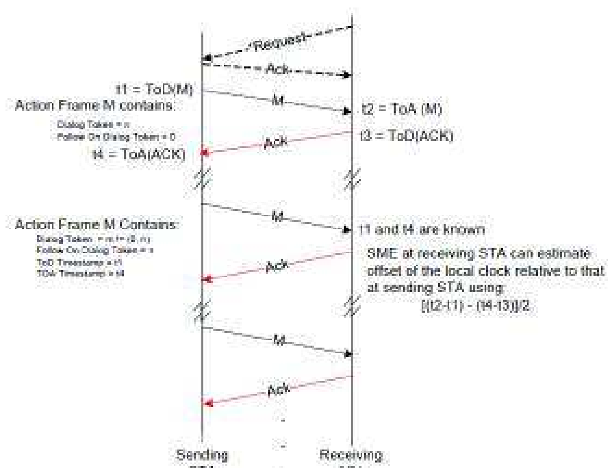

Fig. 4: IEEE std. 802.11v Timing Measurement Implementation

2) Massive MIMO: Classic array processing with MIMO (multiple input multiple output) antennas as surveyed in [10] is focused on accurate DOA estimation. Though the theory is rather mature and that all cellular standards since GSM are prepared for MIMO, it is so far not a big commercially success. One reason may be that the capacity does not scale well with the additional cost. On the other hand, massive MIMO, where the number of antenna elements is an order of magnitude larger than the number of communication links they serve, scales very favorably. This and may other advantages are described in [25]. However, DOA is not computed explicitly in contrast to classic MIMO. This is an area for future research with large potential for super-resolution DOA estimation.

3) Ad-hoc networks: Localization services that are applicable on these networks must meet different demands such as low power consumption, availability, and reliability. That is why some existing services such as GPS cannot be employed on wireless ad-hoc networks. To address this issue, one alternative is to use short-range single-hop localization system. However, there are cases in which reference nodes are not in the range of unknown ones. Then, multi-hop techniques must be taken into account. In these scenarios, beacon positions is broadcasted over multiple hops. This allows estimation of the distance to beacon nodes by calculating hop sizes and number of hops while no direct communication is required where no-direct-communication is an inherit feature of ad-hoc networks.

C. Trend 3: New Infrastructure

The infrastructure illustrated in Figure 5 contains different entities that each of them can affect the measurement resolution drastically. All the devices at the lowest layer are connected to their upper layer devices via a short-range technology such as Bluetooth, ZigBee, etc. At the mean time, devices in the middle layer could vary from a simple User Equipment(UE) acting as a gateway to a Machine Type Communication (MTC) device [26]. Different types of access of the middle devices could be an IP-connectivity to another gateway, cellular access to the AP or even an intra connection to another device of the same layer via a short range technology. this is further elaborated in [27]

1) BLE beacons: Bluetooth Low Energy (BLE) beacons can be low cost tiny computers equipped with Bluetooth radios. More complex hand-held devices such as smart phones can also provide the same functionality. The generic idea is that these devices emit short-range signals that can be decoded by another BLE-enabled device. The distance to the receiving beacon can then be estimated. The possibility of identification of multiple beacons simultaneously in parallel with relative distance calculations of each beacon, location awareness of the device becomes possible. A trend in the BLE beacon industry is to only use proximity for the LBS, that is, a coarsely quantized position.

2) IoT: Internet of Things (IoT) can be seen as a great potential in many lines of research and development. However, massive signaling traffic produced by numerous objects that update their locations, arises new challenges that need to be addressed. Thus, there is a need for appropriate solutions that provide accurate location information while keep the signaling level low.

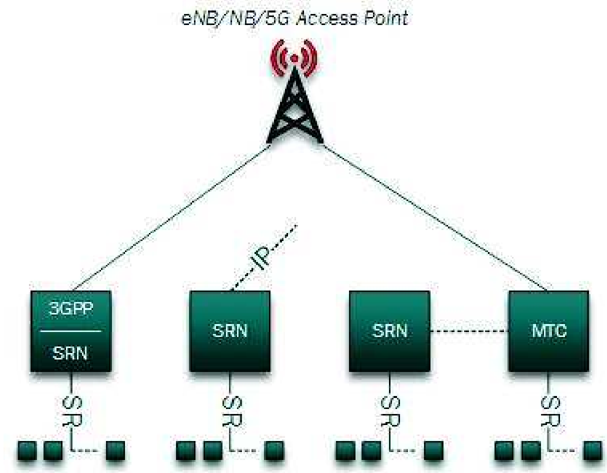

Fig. 5: 5g

3) M2M: Machine to Machine (M2M) networks contain a number of devices such as RFID, sensors, tags, etc. This type of network is employed in different location-based applications ranging from health monitoring to battlefield surveillance. M2M communication networks are self-configurable with the feature of being accessed remotely. The efficiency of approaches for location estimation of M2M network devices can be defined by scalability, whether or not is dependent to GPS systems, range-based or range free property, and error handling capabilities.

4) 5G and Future Radio Network Standards: First of all, 5G should not be seen as an evolution of 4G. The communication capacity will probably increase, but more important is the industrial application and for embedded systems as IoT and M2M. Positioning is one of the most important design specifications.

V. Conclusions

Positioning in devices and gadgets is currently in transformation from "nice to have" to "a must". First, we have safety legislations giving tough specifications on the position information in emergency calls. Then, we have the rapid development of location based services (LBS) which requires position in situations where satellite navigation systems do not work (indoors, underground, etc). Further, a rapidly increasing number of devices connected to the cellular network are not operated by humans. We have the trends of Internet of Things, machine to machine communication, autonomous vehicles and systems, etc, where communication and positioning will be the key enabler for future functions and services.

The purpose of this survey was to describe the over-all picture of how state of the art is organized today (see Figure 1), recent advances in how the fundamental measurements are computed in recent standards, and pointing out new trends. The intention is to provide the fusion community with background information to make relevant simulations and performance analysis, as well as ideas for new research directions.

VI. Acknowledgement

This work is funded by the European Union FP7 Marie Curie training program on Tracking in Complex Sensor Systems (TRAX).

References

[1] D. N. Hatfield, "A report on technical and operational issues impacting the provision of wireless enhanced 911 services," Federal Communications Commission, Technical Report, 2002.

[2] Y. Zhao, "Standardization of mobile phone positioning for 3G systems," *IEEE Communications Magazine*, vol. 40, no. 7, July 2002.

[3] "Wireless e911 location accuracy requirements, fourth report and order," Federal Communications Commission, Technical Report 15-9, 2015.

[4] J. J. Caffery and G. L. Stuber, "Overview of radiolocation in CDMA cellular systems," *IEEE Communications Magazine*, vol. 36, no. 4, April 1998.

[5] C. Drane, M. Macnaughtan, and C. Scott, "Positioning GSM telephones," *IEEE Communications Magazine*, vol. 36, no. 4, April 1998.

[6] G. Sun, J. Chen, W. Guo, and K. J. Ray Liu, "Signal processing techniques in network-aided positioning: A survey," *IEEE Signal Processing Magazine*, vol. 22, no. 7, July 2005.

[7] A. H. Sayed, A. Tarighat, and N. Khajehnouri, "Network-based wireless location," *IEEE Signal Processing Magazine*, vol. 22, no. 7, July 2005.

[8] F. Gustafsson and F. Gunnarsson, "Possibilities and fundamental limitations of positioning using wireless communications networks," *IEEE Signal Processing Magazine*, vol. 22, no. 7, July 2005.

[9] H. Ryden, S. Modarres Razavi, F. Gunnarsson, S. M. Kim, M. Wang, Y. Blankenship, G. A., and A. Busin, "Baseline performance of LTE positioning in 3GPP 3D MIMO indoor user scenarios," in *Proc. International Conference on Localization and GNSS*, June 2015.

[10] Krim and Viberg, "Two decades of array signal processing research: the parametric approach," *IEEE Signal Processing Magazine*, vol. 13, no. 4, July 1996.

[11] F. Gunnarsson, F. Lindsten, and N. Carlsson, "Particle filtering for network-based positioning terrestrial radio networks," in *Data Fusion Target Tracking 2014: Algorithms and Applications (DF TT 2014), IET Conference on*, April 2014, pp. 1–7.

[12] Y. Zhao, "Overview of 2G LCS technologies and standards," in *Proc. 3GPP TSG SA2 LCS Workshop*, London, UK, January 2001.

[13] J. J. Caffery, *Wireless Location in CDMA Cellular Radio Systems*. Kluwer, 1999.

[14] J. Del Peral-Rosado, J. Lopez-Salcedo, G. Seco-Granados, and F. Zanier, "Achievable localization accuracy of the positioning reference signal of 3gpp lte," in *Proc. International Conference on Localization and GNSS*, June 2012.

[15] K. Keunecke and G. Scholl, "Deriving 2d toa/tdoa ieee 802.11 g/n/ac location accuracy from an experimentally verified fading channel model," October 2013.

[16] K. J. Krizman, T. Biedka, and T. Rappaport, "Wireless position location: Fundamentals, implementation strategies, and sources of error," in *Proc. IEEE Vehicular Technology Conference*, June 1997.

[17] W. Xu, M. Huang, C. Zhu, and A. Dammann., "Maximum likelihood toa and otdoa estimation with first arriving path detection for 3gpp lte system," *Transactions on Emerging Telecommunications Technologies*, November 2014.

[18] K. Muralidharan, A. J. Khan, A. Misra, R. K. Balan, and S. Agarwal, "Barometric phone sensors: More hype than hope!" ser. HotMobile '14. New York, NY, USA: ACM, 2014, pp. 12:1–12:6.

[19] G. Liu, M. Iwai, Y. Tobe, D. Matekenya, K. M. A. Hossain, M. Ito, and K. Sezaki, "Beyond horizontal location context: Measuring elevation using smartphone's barometer," in *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*, ser. UbiComp '14 Adjunct. New York, NY, USA: ACM, 2014, pp. 459–468.

[20] A. Kangas and T. Wigren, "Angle of arrival localization in LTE using MIMO pre-coder index feedback," *IEEE Communications Letters*, vol. 17, no. 8, August 2013.

[21] J. Del Peral-Rosado, J. Lopez-Salcedo, G. Seco-Granados, F. Zanier, and M. Crisci, "Analysis of positioning capabilities of 3gpp lte," September 2012.

[22] *IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Std., Rev. Revision of IEEE Std 802.11-2007, March 2012.

[23] "Ieee p802.11-revmc/d3.3," Tech. Rep., October 2014.

[24] "Potential enhancements for indoor positioning," Ericsson, Tech. Rep. R1-150268, February 2015.

[25] F. Rusek, D. Persson, B. K. Lau, E. Larsson, T. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up mimo: Opportunities and challenges with very large arrays," *IEEE Signal Processing Magazine*, vol. 30, no. 1, pp. 40–60, January 2013.

[26] D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "Lte release 12 and beyond," *Communications Magazine, IEEE*, vol. 51, no. 7, pp. 154–160, July 2013.

[27] J. Sachs, E. P. a. M. J. Beijnar, N. and, F. Militano, and P. Salmela, "Capillary networks a smart way to get things connected," *Ericsson Review*, vol. 91, Sep 2014.