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Tactile Localization in mm-WAVE Systems: Channel Measurements Requirements, Challenges and Opportunities

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Abstract. Millimeter Waves (mmWave) have recently attracted a lot of research interest in different domains. Among others, localization using mmWave became one of its major applications. In this paper, the tactile localization concept aiming at reaching sub-cm accuracy is introduced. The main challenges and approaches to realize tactile localization are also presented. The paper will mainly focus on the need for accurate channel measurements in conjunction with the applications opportunities namely in Ambient Assisted Living and indoor environment.

1. Introduction

Millimeter Wave (mmWave) wireless communication systems have recently gained great research interests due to their benefits in terms of spectrum, propagation characteristics, potential applications and services. Basically, mmWave spectrum ranges between 30 GHz and 300 GHz [1]. mmWave research is arising in different applications such as radar, satellite, cellular backhaul, and others. mmWave has also been oriented towards consumer applications in WPAN and WLAN at 60 GHz unlicensed band [2].

Indoor Positioning Systems (IPSs) have also been the center of attention for researchers because of the vast technological enhancement in smartphones and tablets, and the evolving technology of Internet of Things (IoT) as a future service in 5G. For instance, localization is critical for detecting products stored in a warehouse, medical equipment and personnel in a hospital, and firemen in a building, to name a few. With the evolution of mmWave communication systems, IPSs will exploit the infrastructure of future mmWave groundwork to elaborate advanced localization applications. In the literature, many works have dealt with the localization and mapping using mmWave. Particularly, the authors of [4] presented some opportunities and challenges in 5G mmWave for Ambient Assisted Living (AAL).

In this paper, we target tactile localization using mmWave, which is defined as extremely high accurate, reliable and secure localization and mapping reaching accuracy at the sub-cm levels. Therein, we will focus on the main challenges encountered to reach this accuracy and opportunities foreseen by the exploitation of this technology. Among others, we focus on the channel measurements needs, constraints and opportunities. Then, we will complement our work with the main techniques and approaches that could be used to implement tactile localization. The paper will then present the main applications in tactile localization, namely the AAL applications. It is worth mentioning that the paper will focus on indoor environment for the sake of simplicity but many concepts and approaches could be generalized for other contexts.

2. Tactile Localization: Approaches and Observations

Definition: *We inherit the term "tactile localization" from the tactile internet concept. Extreme high accuracy, observability, security and reliability are the main characteristics for tactile localization. Particularly, a tactile localization technology aims at achieving sub-cm accuracy.*

The applications of tactile localization are many, and due to the high accuracy requirements, a tactile localization system is investigated in indoor environments targeting AAL applications.

Currently, many localization approaches and systems are available on the market. But, most of these technologies have not converged towards a unique and standardized solution. As high accuracy is the major requirement, tactile localization should be implemented in wideband systems such that high time-resolution of the channel paths is possible. Consequently, Ultra-Wide Band (UWB) technology is presented as the most promising candidate as it allows for excellent separation between the multi-path components (MPC) [5]. The direct path can also be separated from these MPCs allowing for accurate estimation of the location information. However, UWB technologies operate at low frequencies (3-10GHz), usually with limited power due to interference problems. Moreover, UWB should be implemented as a stand-alone technology for it to be adopted.

Fortunately, the UWB technology could be shifted to mmWave frequencies. In this case, it could be implemented as standalone technology as these bands are still empty or could be coupled with proposed standards such as IEEE 802.11ad. Table 1 gives a summary of the raw possible accuracy of different systems used in localization.

The technical interest in the mmWave based tactile localization resides in different aspects; first, the available bands for operation are wide, which is indeed a requirement for high accuracy. Second, beamforming is one of the important characteristics for localization with high accuracy. The opposite is also true as the beam steering highly depends on the location information. Third, it is possible to transmit with higher power at mmWave frequencies without necessarily degrading other signals, due to the pencil shape of the mmWave beam.

Table 1. Raw localization accuracy of existing systems

System	Bandwidth (MHz)	Frequency (GHz)	Accuracy (Raw)
IEEE 802.11a/g	20	5/2.4	15 m
IEEE 802.11n	40	2.4/5	7.5 m
IEEE 802.11ac	Up to 160	5	1.9 m
LTE Small cells	Up to 100	several	2 m
UWB	>500	3.1-10	0.6 m
IEEE 802.11ad	>2000	58-64	15 cm
UWB @mmWave/ standalone/hybrid	Up to 7000	28/74/72	4 cm

Nevertheless, localization using mmWave faces different challenges. First, the scattering richness (seen at low frequencies) is limited at mmWave as very few bounces reach the target with acceptable power. Second, the absorption and the path loss decay at mmWave are critical, limiting the coverage and localization approaches and techniques and adding a cumbersome complexity to these approaches. Third, the localization at mmWave frequencies highly depends on the environment, hence any change in this environment will lead to high localization errors.

Technically speaking, in order to address the location dependence of received signal, a geometry based channel model should be supported. This allows for deep analysis of the MPC signals and the different obstacles and reflectors in the environment. In UWB, different signal models have been proposed. We mention here the work in [5], which provided some insights about the geometry dependence in the signal model. A received signal in UWB can be expressed as:

$$y(t) = \sum_{i=1}^{L} \alpha_i e^{j\theta_i} x(t-\tau_i) + x(t) * v(t) + w(t) \tag{1}$$

In (1), α_i , θ_i and τ_i represent the MPC channel amplitudes, phases and delays, respectively; The three parameters could be used separately (or jointly) to develop localization approaches based on Received Signal Strength (RSS), Time of Flight (ToF), or Angle of Arrival (AoA). $x(t)$ is the transmitted signal and $w(t)$ is the additive white Gaussian noise. The signal $v(t)$ represents the diffuse multipath, which acts as a source of interference to the observed elements at the receiver, mainly for the angle estimation. It acts as an additional element to the receiver originating from false sources. However, it has been shown that the AoA approach achieves the best accuracy in mmWave due to the wide AoA spectrum diversity [6], but affected by the diffusion multipath. Hence, a good estimate of the diffuse multipath should be considered. To this end, and again due to the channel characteristics at mmWave, an antenna array with controllable beam should be implemented. This offers high directivity of the received signal and allows a good estimation of the different MPCs, hence an accurate location. The separation between MPCs allows also for the estimation of obstacles locations and limits as shown recently in [7]. This opens the door for different applications, namely in AAL.

3. Channel Characteristics in mmWAVE: requirements and challenges

3.1 Channel Characteristics and Measurements

The channel characteristics at mmWave are quite different from those below 6 GHz. Indeed, the receiver antennas aperture at mmWave is smaller; This makes the received signal power smaller than at low frequencies. Moreover, the signal at mmWave highly suffers from the deep shadowing effect due to the use of mmWave length. To address this problem, mmWave systems are equipped with steerable mechanisms with high-gain directive antennas or adaptive beamforming by promoting the use of antenna arrays. As the diversity is limited in mmWave, the equivalent channel behaves as a quasi-optical channel, i.e., the line of sight (LoS) factor is dominant. Thus, mmWave channel models take into consideration no more than double-bounce reflections since higher order of bounces for no line of sight (NLoS) paths are deteriorated. In this case, the value of L in (1) reduces to 3.

Moreover, the characteristics of the channel at mmWave frequencies showed that reflections don't generate significant amount of scattering, and that the transmitted beam will have the same directivity after reflections with slight scattering. Hence, Snell's law holds in terms of the equality between the angles of departure and incidence upon reflection as shown in Figure 1.

All these channel characteristics are very useful for tactile localization. However, the need for accurate channel measurements and real channel models is considered, without no doubt, as the most challenging task. In the literature, different channel measurements are proposed. The world-leading channel measurements are achieved by Rappaport & al. at different frequencies. We particularly mention their work in [8] and [9]. In [8], the large-scale path loss and RMS delay spread at 28 GHz and 73 GHz are provided. In [9], the authors presented an extensive work on channel measurements at 73 GHz. This includes important technical details on the effect of antenna polarization, reflection coefficients, environment, etc. They have also provided some key elements for channel modeling and simulators. In [10], the authors presented frequency domain measurements with 1 GHz bandwidth and 1 ns time resolution. In [11], they built and used a time-domain channel sounder to measure and model the channel characteristics in mall/shopping environment. The reader may refer to [12] for more information on channel measurements in indoor environments. But, it is easy to deduce that the challenges and needs for accurate channel measurements leading to tactile localization are still numerous as detailed in the next section.

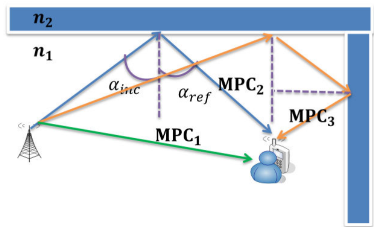

Figure 1. MPC components and Snell's law @mmWave

3.2 Channel Models

Extensive channel models have been proposed and successfully used in the literature, mainly for frequencies below 6 GHz, as they are presenting important bricks for the evaluation and success of wireless systems. Undoubtedly, this trend has started and will continue at mmWave. However, to be useful, these mmWave channel models must represent real channel measurements and present high accuracy of the environment. Moreover, their implementation must be cost and complexity efficient. Surely, the level of accuracy depends on the application and the need. For instance, to evaluate the system performance of a wireless communication algorithm, a fair accuracy could be acceptable. However, it becomes a major constraint when targeting tactile localization.

Two different approaches have been considered for mmWave channel models: stochastic and map-based. The stochastic model is useful in predicting probabilistic parameters of transmission algorithms. Hence, it provides good understanding of the mobile network behavior. Stochastic channel models define the different parameters in a stochastic manner without specifying the locations of scatterers in the environment. Map-based channel models, widely defined through Ray Tracing, define the locations (which might be random) of scatterers in a given environment based on the geometric ray dispersion model and uses reflection and refraction concepts to determine different parameters (AoD, AoA, delay, etc.) for each ray. Some of its advantages over a stochastic-based channel model are that various carrier frequencies, realistic large scale and small scale parameter correlations, and dynamic modeling are automatically supported due to the physical modeling techniques used. The main issue or disadvantage of this model is that it depends on the knowledge of the geographical environment and on the different objects therein. The problem becomes even more pronounced in mmWave as different objects have different reflection coefficients and absorption ratios. Moreover, the latter depends on different parameters [9][12]. To partially solve this problem, a stochastic Map-based model including a set of possible environments could be proposed such that different stochastic objects and components could be added to the map-based model.

Another important point concerns the relation between the models and localization techniques and approaches. From this perspective, for instance, a map-based model is more appropriate as it describes several behaviors of the channel and gives more insights and better representation of the environment for localization purposes. In general, the ray tracing tool is the most appropriate as it provides good environment modeling using ray diffusion and the tracing approach [12]. Indeed, the ray tracing (simulator) approach is based on real channel measurements and various parameters from the different objects and environment to create a description of the transmission. The importance of this model is that it is location dependent and captures different parameters (to be configured) such as antenna polarization and patterns.

4. Challenges and Requirements for Tactile Localization

The benefit behind the use of mmWave band is due to the availability of a very large bandwidth (7 GHz) and hence, achieving accurate range measurements. Even though channel measurements and models have been done at mmWave, the requirements for accurate channel considerations used in tactile localization are still open questions to be solved. A non-exhaustive list includes the following:

1. There is still much work to be done on localization using mmWave and the theoretical accuracy limits are still not clear for all environments and technologies. There is no doubt that these limits should be defined and confirmed by measurements as they open the door for subsequent applications.
2. A larger bandwidth, expected to be used in mmWave, leads to improved temporal resolvability of rays, which in turns leads to improved localization accuracy never reached before (even a mm accuracy). However, this requires an accurate resolvability of these rays and consideration of intra-cluster delay spread and power distribution.
3. Various objects (e.g. humans, foliage, glass, etc.) cause strong and different attenuation levels, which change the behavior and power spectrum of the metrics used for localization (AoA, ToF, RSS) hence, they should be accounted for in developing algorithms aiming tactile localization.
4. Time and spatial correlation of the channel measurements should be accounted for in mmWave. This should also include different propagation characteristics (LoS, OLoS, NLoS).
5. Different antenna array polarization and types should be also included in the channel model. Moreover, a big challenge consists in modeling the antenna manifold. The questions here is whether the standard antenna

manifold should be kept or should the model include arrival/departure angles with delays across the array and consider a spherical wave assumption.

6. Targeting 3D localization as required by different standards (E911) requires the adoption of accurate 3D channel measurements and models. The work here is still at its infancy but it is worth mentioning the work in [14] where the authors have practically presented the first practical 3D channel model based on geometry environment (Ray-Tracing) working at mmWave.
7. Privacy and security in tactile localization are still open issues in localization. Lightweight cryptography and security protocols might be the best solutions for tactile localization in IoT applications but advanced protocols might be needed for sensitive localization data.

5. Applications in Tactile Localization

Indoor positioning and navigation for mobile devices is a market with expected size of USD 4 billion in 2018. AAL are by far the most promising applications using tactile localization. AAL environments are generated from "ambient intelligence" to perform smart and automated machine-human interactions. A typical example here concerns the use of tactile localization for tracking and monitoring. The technology could be also used for presence detection and context inference. In this case, one would estimate the reflection coefficient of the different objects in a room to detect abnormal situations [7]. In any case, tactile localization will be the heart of AAL and seamless emergency services. One can foresee different health related applications for both monitoring and robotic intervention. Some of these applications are already there. The reader might refer for instance to [15] where the mmWave based localization is able to locate and track a pen with less that 8mm error i.e. performing tactile localization accuracy.

In conclusion, the number of applications in mmWave based tactile localization will surely explode once the tactile accuracy is reached. This should be one of the main research topics in the near future.

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