Development of Room Geometry Estimation Technique Utilizing Millimeter-Wave Radio Systems

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Abstract: For realizing automated monitoring of the behavior and preferences of residents for smart homes/smart building applications, device-free localization techniques using radio propagation characteristics have gained interest. In such techniques an environmental information should often be known in advance. This study developed the multi-dimensional Kirchoff migration method to estimate a room geometry for indoor localization and the estimation accuracy was evaluated by ray-tracing simulations. By utilizing millimeter-wave radio systems, multi-dimensionality in terms of time-of-flight and angle-of-arrival/departure and high resolution in channel impulse responses offer high estimation accuracy. Moreover, the feasibility was demonstrated via the laboratory test measurements using our channel sounder.

Keywords: Millimeter-wave, Kirchoff migration, Environmental imaging, Beamforming, Angle resolution

Classification: Antennas and Propagation

References

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1 Introduction

By technical progress of IoT (internet-of-things) a highly advanced automated home environment for living will be on hand in near future. Here, indoor localization and mapping will be playing an important role [1]. Various localization/positioning techniques have been developed, but the performance of them is often considerably degraded relying on actual multi-path propagation environments. Further, device-free localization (DFL) technique should be preferable for smart home/building applications, but most of existing techniques are device-based, namely, a person must carry an electronic device. The authors have proposed an efficient DFL technique using a novel radio tomographic imaging (RTI) method, called Multi-path RTI [2] assuming the utilization of millimeter-wave (mm-wave) radio systems such as fifth-generation (5G) mobile and IEEE 802.11 ad/ay WiGig systems which currently attract a great deal of attention. The Multi-path RTI can drastically reduce the number of anchor nodes by using the virtual anchor nodes created by multiple reflections.

In many DFL techniques including Multi-path RTI, it is supposed that the environment information is perfectly known in advance. Moreover, automatic acquisition should be preferable for ease of the end-users who do not have sufficient technical knowledge such as elderly people [3]. This study describes a multi-dimensional Kirchhoff migration (MDKM) to estimate a room geometry extending the existing Kirchhoff migration (KM) [4] method.

The original contribution of this study is three-fold. First, the MDKM method, a new room geometry estimation method using mm-wave systems is developed. Second, the accuracy of the positions of the virtual anchors (VAs) generated by single-bounce reflection is evaluated as a performance measure by ray-tracing simulation and the advantages against the conventional KM method are shown. Third, the feasibility of the proposed method is demonstrated via the laboratory test measurements.

2 Multi-Dimensional Kirchhoff Migration

In this study, it is assumed that mm-wave ultra-wideband (UWB) wireless transmission systems are used where the large signal bandwidth and very narrow beamwidth offer high resolution time-of-flight (ToF) and angle-of-arrival/departure (AoA/AoD) estimation. The measured channel impulse response model is expressed by superposition of multiple plane waves as

\[ h(\tau, \phi_T, \phi_R) = \sum_l \alpha_l e^{j2\pi f_c \tau_l} a_\tau (\tau - \tau_l) a_R (\phi_R - \phi_{R,l}) a_T (\phi_T - \phi_{T,l}) \]  

(1)
where $\alpha_l$, $\tau_l$, $\phi_{R,l}$, $\phi_{T,l}$ denote the amplitude, delay, AoD, and AoA of the $l$-th wave. $a_\tau$ denotes the auto correlation function of the probing signal, $a_R$ and $a_T$ denote the angular beam patterns at receiver and transmitter, respectively. It is obvious that imaging performance should depend on the resolutions (selectivity) of $a_\tau$, $a_T$ and $a_R$.

The KM [4] estimates the room geometry by imaging the surrounding large objects such as a wall while a mobile station (MS) as an agent is moving around the base station (BS). It forms an image using the object distribution function of distance. When the channel impulse responses are measured at $N$ different MS positions, the object distribution function at a point $p = (x, y, z)$ is obtained as

$$o(p) = \frac{1}{N} \sum_{n=1}^{N} R_n \left( \frac{d_n(p)}{c} \right)$$

where $p_{MS,n}$ and $p_{BS}$ denote the $n$-th MS position and the base station (BS) position, respectively, and $d_n(p) = |p - p_{MS,n}| + |p - p_{BS}|$. $R_n$ denotes the power delay profile (PDP) at $n$-th MS position expressed as $R_n(\tau) = \sum_{\phi_T} \sum_{\phi_R} |h_n(\tau, \phi_T, \phi_R)|^2$. $c$ denotes the velocity of light.

In this study, we propose the MDKM that is extended to use joint information of ToF and AoA/AoD estimation. The object distribution function at a point $p$ is obtained as

$$o(p) = \frac{1}{N} \sum_{n=1}^{N} R'_n \left( \frac{d_n(p)}{c}, \varphi_{BS,n}, \varphi_{MS,n} \right)$$

where $R'_n$ denotes the angle-delay power spectrum (ADPS) at $n$-th MS position expressed as $R'_n(\tau, \varphi_T, \varphi_R) = |h_n(\tau, \varphi_T, \varphi_R)|^2$. $\varphi_{BS}$, and $\varphi_{MS,n}$, denote the direction of the point $p$ from the BS and MS at the $n$-th measurement.

Fig. 1a illustrates the concept of the proposed method where it can be seen that the imaging performance should be determined by the delay resolution ($\Delta \tau$) and angle resolution ($\Delta \phi$) in the ADPS. Fig. 1 shows an example of the image results of the existing and proposed methods. The blue square marker and the red circular markers represent the positions of the BS and MS, respectively. The wall is depicted in a rectangle. These figures clearly illustrate the advantage of the proposed method. Specifically, it offers a more accurate image along the wall of the room. It is obvious that in the proposed method jointly imaging with ToF and AoA/AoD information improves the accuracy.

3 Performance Evaluation

By extensive ray tracing simulation the room geometry estimation accuracy was evaluated to estimate the performance of actual mm-wave systems which can have various ToF and AoD/AoA resolutions. The ray tracing simulations were performed on a simple room model with four walls, using imaging method, with three reflections and a single diffraction. The BS was placed in the center of the room, and the MS route consisted of 20 points in a square or circular track at approximately 1 m from the center of the BS. In this evaluation, we assumed that the exact MS positions on the measurement track
are perfectly known, thus those two types of track were chosen for ease of measurement. In addition, this study assumes that the information of ToF and AoD should only be available because an antenna array is usually not fully equipped in an MS.

The estimation of the positions of the VAs generated by single-bounce reflection is used as a performance measure. To obtain the positions of the VAs, the raw image was converted into a binary image. Then, merging some isolated images of the scattering objects greater than a certain level, the square shape of the room were determined as shown in Fig. 2a. Finally, a VA was obtained as an image node with respect to one of the determined wall. Comparing the positions of the estimated VAs with their ideal positions, the average error $\varepsilon_{VA}$ were obtained. Fig. 2b, Fig. 2c shows the results. It can be seen that the average position error of the four walls is less than 0.3 m when the bandwidth is greater than 1.2 GHz and the beam width is smaller than 60 deg.

4 Experimental Validation

The MDKM method was validated via a laboratory test measurement using mm-wave directional channel sounder [5] which has 400 MHz signal bandwidth at the center frequency of 58.5 GHz. The angle domain was acquired by rotating directive horn antennas of which half-power beamwidths were 12 and 30 deg, at transmitter and receiver, respectively. Fig. 3a shows the floor plan of the laboratory. The channel impulse responses were measured at 12 MS points where the BS was fixed at the center of the room and the MS was moved along a square track around the BS. Each antenna was placed on a tripod at 1.3 m off the floor. Fig. 3b and 3c show the simulation and experimental results, which shows that the proposed method is applicable to the actual environment because both images are well matched.

5 Conclusion

In this letter, we summarize the MDKM method using mm-wave radio systems capable of high resolution ToF and AoA/AoD estimation. The performance evaluation results show that the maximum performance is about 0.1 m, and the applicability of the method is demonstrated by comparing the
Fig. 2: Average positioning error in two different measurement tracks.

Fig. 3: Comparison between simulation and measurement results (bandwidth: 400 MHz, beamwidth: 12 deg.)

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