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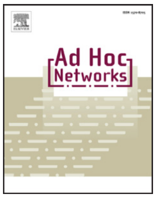

Environment-aware localization for wireless sensor networks using magnetic induction[☆]

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ABSTRACT

The Magnetic Induction (MI) communication techniques can enable or enhance many wireless applications in the complex environments where line-of-sight (LOS) links do not exist. The critical position information of each wireless device can also be derived by the same MI systems without additional hardware or infrastructure. However, while MI signals can penetrate most of the transmission media without significant attenuation or phase shifting, the obstacles with high conductivity can still influence the signal propagation, which incurs additional positioning errors in the MI-based localization. To address such challenge, this paper develops an environment-aware MI-based localization technique for wireless sensor networks in complex environments with significant amount of high-conductive obstructions. First, the system architecture of the MI-based environment-aware localization and the MI channel is introduced. The environment-aware capability is realized by analyzing the unique MI response information gathered by each MI-based sensor node. Then, a joint device localization and environment sensing algorithm is developed to estimated the position of each device in the network as well as the distribution of the high-conductive objects. Finally, the performance of the proposed solution is validated through both computer simulations and real-world experiments.

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1. Introduction

Due to the lack of the line of sight to satellites, the GPS, which is widely used to obtain the position information in outdoor environments cannot work in many places such as underground tunnels [2,3], underwater environments [4] and indoor environments [5,6]. The localization based on wireless sensor networks (WSN) becomes one of key technologies to address the challenges in these scenarios [7–10]. Based on the signal strength or phase of the received signal obtained by the communications in the network, the internode distance can be estimated and then the position of each node can be determined by geometric calculations [11–13].

Numerous technologies including received signal strength indication (RSSI) [13–15], time of arrival (TOA) [16], and angle of arrival (AOA) [12,17] can be utilized for the localization of WSNs. By capturing the information from the internode communications, such as signal strengths and phases, the internode distances or orientations can be estimated by relating them with the channel model of the signal propagation. The positions of the sensor nodes are then estimated based on their relative positions. However, the problems exist when we apply these technologies in the complex environments. First, traditionally the localization technologies for the WSN are based on the EM signals received in the sensor nodes. Due to the rapid attenuation of the EM signal strength in the RF-challenging environments, such as underground and underwater environments, the sensor nodes can only be localized in very limited distance [18]. Second, existing localization techniques for WSNs are mainly based on deploying anchor nodes or RFID tags at predesigned positions, which requires pre-installed infrastructures in the environments [11,19–21]. However, the pre-installed infrastructures are not feasible in many applications, such as the military or law enforcement missions in indoor environments and the exploration tasks in underground or underwater environments. Moreover, the complex environments, such as indoor and in-pipe environments, usually consist of reflectors like walls, pipes, and rebar structures. The localization error increases as the distance from the anchors or tags increases due to the severe propagation conditions of the radio channel influenced by the signal reflections. To address the problems caused by signal reflections and improve the

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[☆] A much shorter preliminary version of this paper appeared in [1].

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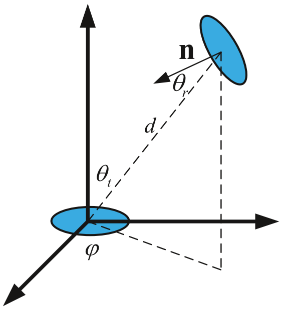

Fig. 1. MI technique based on two coupled coils.

localization accuracy, fingerprint database for localization is built by aforehand training measurements to better relate the signal strength with the device position [22,23]. However, such strategies are based on aforehand experimental measurements and not applicable for unknown or dynamic environments.

To address the problems of the signal attenuation in RF-challenging environments, the magnetic induction (MI)-based communication has been proposed [24–28]. As shown in Fig. 1, the MI communication uses a small loop to generate magnetic field in high frequency (HF) band and receive the signal by capturing the induced current in another coil. Instead of using propagating EM waves, MI technique utilizes the near field of low frequency electromagnetic field to realize the wireless communication. Hence, it is not significantly influenced by the complicated underground or underwater medium because the magnetic permeability of in these medium is almost the same as that in air. Moreover, the MI channel is also reliable and determined since the MI signals are not easily reflected or scattered by the random obstructions. Due to the lower operating frequency and simple antenna design, the MI transceiver also has very low cost. As a byproduct of the wireless communications, the same MI system can readily provide localization capability without any additional hardware or cost.

Although MI-based communication has more tractable channels, it is still influenced by high-conductive objects in the complex environments. For example, if the MI coils are located near large metallic facilities, such as reinforcing bars, metallic pipes, and metallic walls, the magnetic field can not penetrate them. Eddy currents will be generated on these objects and they will excite new magnetic field to affect the primary field. Therefore, the influence from those high-conductive objects need to be considered when we apply the MI-based localization in such complex environments. However, since the MI coils are sensitive to those high-conductive objects nearby, it is possible to use the MI coil as a “radar” to detect and estimate those high-conductive objects. The magnetic field generated by the eddy currents on those objects will also be detected by the MI coil itself. By capturing the feedback by the MI coils, the distribution of the high-conductive objects can be estimated and it can be used as the environment-aware information to develop localization algorithms.

In this paper, an environment-aware localization strategy is developed for MI-based wireless networks in complex environments with arbitrary number of conductive objects. Specifically, the influence of conductive objects on the MI channel in complex environments is first investigated and then an environment-aware algorithm for the conductive objects is developed. Based on the environment-aware measurement obtained by the MI nodes, a joint device localization and conductive-object tomography algorithm is developed to estimate the position of the wireless devices as well as the distribution of conductive objects. In particular, the distribution of the conductive objects is quantized by the newly defined intensity magnitude. By adding the intensity magnitude as an input of the localization algorithm, the internode distances and orientations are determined and then the coordinates of nodes can be estimated. Finally, through numerical simulations and real-world experiments, the localization accuracy is analyzed and the environment-aware localization technique is validated to be better than that without the environment-aware capability.

The remainder of this paper is organized as follows. The related works are presented in Section 2. The preliminaries, including the system architecture and the channel modeling of MI communications, are introduced in Section 3. Then, we analyze the influence from the conductive objects in the complex environments to the MI channel in Section 4. In Section 5, the localization algorithms based on the environment-aware result is presented. After that, we present the system implementation, experimental result and discussion in Section 6. Finally, this paper is concluded in Section 7.

2. Related work

The wireless sensor network becomes a solution for the localization in complex environments where the GPS does not work due to the lack of the LOS (line of sight) link to the satellites. However, the localization for WSNs based on EM waves has problems when applied in the complex environments. In the wireless channel consisting of the RF-challenging propagation medium, such as underground and underwater, conventional wireless techniques based on the EM waves do not work due to the rapid attenuation of signal strength [9]. To address this problem, the wireless communication technique based on MI for RF-challenging environments is proposed in [25], after which many novel applications using MI-based communication are presented, including underground [26], underwater [24], pipelines [29,30], and reserviors [27]. The availability of MI-based communication is demonstrated and evaluated by the experimental research in [28]. The preliminaries of the MI-based localization are provided by these research.

Another problem of traditional localization strategies is the requirement of pre-installed infrastructures. In the complex environments, anchors or RFID-tags are usually used to localize the mobile sensor nodes [5–8,19–21]. However, these strategies can be used in the known indoor environments but difficult to be applied in unknown or dynamic environments. Moreover, the localization error significantly increases as the distance from the anchors or tags increases due to the influence of the signal reflections. To address the problem caused by the signal reflections, fingerprint database for localization is built by aforehand training measurements to better relate the signal strength with the device position so that the localization performance can be improved [22,23]. However, since these techniques require aforehand knowledge and numerous facilities, they are not easy to be applied in the unknown or dynamic environments.

Research on MI-based localization is developed in [31,32]. In [31], researchers propose methods for object localization using beacons of low frequency quasi-static magnetic field. To localize the object, the magnetometer readings on the object are processed to estimate the magnitude and phase of the received beacon signals. Due to the utilization of low frequency magnetic field, the signal can penetrate foliage, soil, buildings and has no direct influence by bad weather conditions and diurnal variations. In [32], the MI-based localization is utilized to solve the problem of RF-challenging environments. In this research, the magnetic induction and acoustic wireless communications are combined to localize the drag anchors in the seabed. The environments in these scenarios are considered as homogeneous environments, which do not have any high-conductive objects to affect the magnetic field generated by the MI coils.

Although the MI signal has more stable and penetrable channel for the localization, it is still influenced by the high-conductive

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