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MST-based topology control with NLOS location error compensation for location-aware networks

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ABSTRACT

The topology control algorithms can improve the network capacity and network lifetime in location-aware networks. The topology control algorithms require accurate locations of mobile nodes or distances between each of the mobile nodes. The IEEE 802.15.4a-based location-aware networks can provide precise ranging distance between two mobile nodes. The mobile nodes can obtain their accurate locations by using accurate ranging distances. However, in the IEEE 802.15.4a networks, the ranging distance has a large measurement error in non-line-of-sight (NLOS) conditions. In this paper, we propose MST-based topology control with NLOS location error compensation algorithm to improve location accuracy and prevent mobile nodes from connecting to unstable links in NLOS condition. Performance evaluation shows the proposed algorithm constructs a topology map which has low location errors with considering the instability of NLOS links in NLOS condition.

1. Introduction

Wireless sensor networks (WSNs) is a very popular solution for home automation, smart office, and environment monitoring [1]. In WSN, the energy conservation is very important because mobile nodes generally use small batteries as a power source. Topology control is an efficient method that can prolong network lifetime, improve communication efficiency. It can remove inefficient wireless links to reduce energy consumption and increase network capacity in WSN [2,3]. Most topology control algorithms assume that all mobile nodes know their exact locations or the distance between each mobile node. Topology control algorithms can construct topology map in location-aware networks [4].

In location-aware networks, nodes can passively or actively determine their locations. Based on location awareness, the networks can provide personal location tracking system. The design of location-aware networks requires the capability of peer-to-peer ranging distance measurement to estimate location. Mobile nodes which do not know their locations can estimate their locations based on ranging distance measurements from reference nodes which know their exact locations. There are five main methods of peer-to-peer ranging distance, time-of-arrival (TOA) [5,6], time-difference-of-arrival (TDOA) [7], received-signal-strength-indication (RSSI) [8], near-field-electromagnetic ranging [9], and angle-of-arrival (AOA) [10]. Ranging in WSNs has some difficulties because of the constraints of mobile nodes. TOA and RSSI are the most widely used ranging methods in WSNs. The IEEE 802.15.4a standard presents the TOA with two-way ranging method [11]. The standard includes all the hardware and MAC-layer functionalities required to perform distance estimation. Symmetric double sided two-way ranging (SDS-TWR) is a distance estimating methodology that is based on the precise time measurements of signal propagation delay between two mobile nodes [12,13]. The IEEE 802.15.4a networks can provide localization solution for location-aware networks.

The indoor environments contain various obstacles which cause non-line-of-sight (NLOS) conditions. In the IEEE 802.15.4a networks, the ranging distance may have a large measurement error in NLOS conditions. We implemented experiments in NLOS conditions with NanoPAN 5375 devices [22]. Through the experiments, we observed that the ranging distance has a large bias error in NLOS conditions. In NLOS conditions, the IEEE 802.15.4a-based location-aware network has large scale location error because of the NLOS bias ranging distance error. The large scale location error causes problems in the topology construction, where the instability of NLOS links is not considered.

To solve the problem, we present the minimum spanning tree (MST)-based topology control algorithm that can compensate

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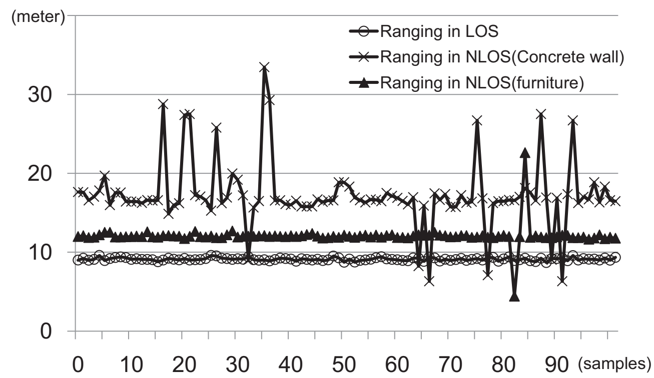

Fig. 1. Ranging measurement result in LOS and NLOS condition.

location errors in NLOS conditions [14]. The proposed algorithm detects location errors by comparing the difference between two MST topologies: one is a MST topology based on the estimated locations, and the other is a MST topology based on the ranging distances. Once the difference is detected, the node finds three neighbor nodes which have their exact locations. Next, the node estimates its location by the trilateration method. In the trilateration, the node uses the exact locations and ranging distances from the neighbor nodes. Performance evaluation shows the proposed algorithm constructs the location-aware network which has low location errors in NLOS conditions. In addition, the proposed algorithm builds the topology map with considering the instability of NLOS links.

2. Problem statement

In the indoor environments, there are many obstacles such as furniture, concrete walls, doors and objects. The obstacles create NLOS conditions, and they degrade the accuracy of locations in IEEE 802.15.4a-based location-aware networks. To analyze the NLOS effect, we implemented experiments in NLOS conditions. In the experiments, we measured the ranging distances by using SDS-TWR and the data packet reception ratio (PRR) between two mobile nodes. The real distance between two mobile nodes is 10 m. To generate various NLOS conditions, we placed a concrete wall and furniture between two nodes for each experiment. In this paper, we assume all nodes are in static condition.

Fig. 1 shows the ranging distance measurement results. The ranging distance is close to the real distance in the LOS condition. However, the ranging distance has large bias and irregular fluctuation in the NLOS conditions. As shown in Table 1, the ranging distance has the largest bias error when the concrete wall is placed between two nodes. The PRR results in the NLOS conditions are lower than in the LOS condition. The number of retransmissions and the energy consumption are increased in the NLOS conditions.

MST-based topology control algorithm uses the location information of mobile nodes to construct a topology. In the MST-based topology control algorithm, the cost of the edge is defined by the Euclidean distance. In NLOS conditions, the MST-based topology control algorithm has problems caused by the location error. The MST-based topology control algorithm does not consider the instability of NLOS links. Transmission failures are occurred by the NLOS links. To remove NLOS links, the XTC uses the signal attenuation as the cost of the edge to construct the topology [15].

Table 1
Experimental result in LOS and NLOS condition.

Description	LOS	NLOS	NLOS
Obstacle	Open space	Furniture	Concrete wall
Ranging method	SDS-TWR	SDS-TWR	SDS-TWR
Distance between devices	10 m	10 m	10 m
Average ranging distance	9.12 m	12.05 m	17.63 m
PRR	100%	82.5%	58.5%

The MST-based topology and XTC topology construction results in NLOS conditions are shown in Fig. 2. In Fig. 2(a), if node u has accurate location, it is connected to node w. If node u has inaccurate location, as shown in Fig. 2(b), the MST-based topology may produce transmission delay and increase the number of transmissions. When node w tries to transmit a packet to node u, node w sends the packet to node y, and node y retransmits the packet to node u. As shown in Fig. 2(c), XTC considers the instability of NLOS links. However, it does not correct the NLOS location errors. It may cause transmission failures in the geographic routing protocol for location-aware networks [16]. In Fig. 2(d), the topology construction considers the instability of NLOS links, while it corrects the location error in NLOS condition for the location-aware networks.

3. Proposed algorithm

We propose the MST-based topology control with NLOS location error compensation for the location-aware networks. We assume the location-aware network consists of the reference nodes which know their locations and the mobile nodes which do not know their locations. The proposed algorithm has the following phases: neighbor table construction, topology construction, and location error correction.

3.1. Neighbor table construction

Each mobile node constructs a neighbor table. The neighbor table consists of the neighbor node information: the node ID, estimated location, and ranging distance $\tilde{d}(\cdot)$. The ranging distance $\tilde{d}(\cdot)$ is obtained by ranging from a neighbor node. To estimate the locations of mobile nodes, the reference node periodically broadcasts a packet with its location information. To estimate the location, we use the least square estimation (LSE) localization method [17–19]. The estimated location can be obtained by the following optimization equations (Fig. 3):

$$\hat{x}_i = \underset{X \in \theta}{argmin} \sum_{i=1}^{N} (\| K - p_i \| - \tilde{d}_{ij})^2 \quad (1)$$

Where X is the network area, N is the number of the reference nodes, p_i is the location of reference node i, $\tilde{d}_{ij}$ is the ranging distance between reference node i and mobile node j, and $\|\cdot\|$ denotes the Euclidean norm. The mobile nodes divide the network area (X) into small square cells (θ). K is the set of locations which corresponds to the center of each cell θ. $\|K - p_i\|$ is the distance between reference node i and the center of each cell. The mobile nodes calculate the distance error between real distance $\|K - p_i\|$ and ranging distance $\tilde{d}_{ij}$. Using the Eq. (1), the mobile nodes estimate $\hat{x}_i$ which are close to their real locations. After estimating the location, the mobile nodes attach their estimated locations on the ranging request packet and broadcast the packet. Once the mobile node received ranging request packet from a neighbor node, it records the estimated location of the neighbor node. It starts measuring ranging distance with the neighbor nodes. The mobile node records the ranging distance on its neighbor table when the procedure has been finished. Next, the mobile nodes broadcast their neighbor tables while receiving the neighbor tables from their neighbor nodes.