Wireless Sensor Network Based Mobile Tracking System

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Abstract: Mobile target tracking through large-scale wireless sensor networks (WSN) demands a large number of reference nodes, which is not feasible for resource-constrained WSNs. This paper proposes a resource-efficient mobile tracking system which integrates connectivity-based range-free approach and Received Signal Strength (RSS) based ranging approach to improve the tracking performance while reducing the specialized hardware requirement. In our proposed system, regulated hop-count values between static unknown nodes and reference nodes in the targeted area of interest for mobile tracking are first estimated in the network configuration phase. Then, location of the mobile target is tracked based on the regulated hop-count values and the available RSS measurements from its surrounding nodes at each tracking point without any extra hardware. Additionally, estimated location is enhanced by correcting with the known information of maximum velocity of the mobile target. Simulation and experimental results show that the proposed system offers preferable mobile tracking performance with minimum reference node utilization in both small-scale and large-scale networks.

Key words: Mobile tracking, WSN, regulated hop-count, RSS.

1. Introduction

Accurate and low-cost location tracking in WSNs plays an important role in applications like habitat monitoring, military surveillance and disaster relief. Existing WSN localization schemes can be categorized into two groups: range-free [1] and ranging or range-based [2] approaches. Range-free schemes determine the node's location by using connectivity information or number of hops (hop-count) between nodes without any specific hardware support. Although they offer lower accuracy than ranging approaches, they give low cost and less power consumption solutions. More precise location estimation can be achieved with ranging approaches which are typically based on RSS, time-of-arrival (TOA), time-difference-of-arrival (TDOA), or angle-of-arrival (AOA), but they require specialized hardware for ranging, thus consuming more power and cost which is not suitable for resource-constrained WSNs.

Recently, RSS has become a standard feature in most of the wireless devices without any extra hardware requirement. In fact, RSS-based mobile tracking approach becomes one of the most popular and cheap techniques. Typically, an RSS-based mobile tracking approach usually consists of a set of static nodes with known location information, referred to as reference nodes. The tracking algorithm tries to continuously estimate the mobile target's location from the RSS measurements between the mobile target and its neighboring reference nodes [3], [4]. Since existence of multipath fading, reflections, diffraction and interference highly affects the correspondence between the RSS and relative distance, more works [5], [6] are proposed to minimize the dynamic fluctuation of the radio signal received from each reference node.

However, existing RSS-based mobile tracking approaches require extensive channel calibrations and their applicability is limited to the targeted network environments. Significantly, at each tracking point, there must be at least three reference nodes inside the radio range of the mobile target. For tracking through a large-scale WSN, a high number of sensor nodes have to be attached with specialized localization hardware since manual configurations of locations for these nodes are not feasible for large-scale networks.

In this paper, we propose an efficient mobile tracking system which minimizes the utilization of reference nodes and improves the localization accuracy without any extra hardware. The main motivations and contributions of this paper are as follows.

1) Unlike existing works which need a large number of reference nodes for mobile tracking through large-scale WSNs, we propose an efficient solution which requires only three or four reference nodes.
2) Previous cost-effective tracking approaches utilize either connectivity information or RSS measurements to track the location of the mobile target. In contrast to this, we integrate connectivity information and RSS measurements in order to improve the location tracking accuracy.
3) An efficient location correction method is applied in the proposed system which shows significant improvement in the target tracking performance.

The rest of the paper is organized as follows. Section 2 presents the detailed workflow of the proposed mobile tracking system. Simulation and experimental based performance evaluations are discussed in Section 3 and finally in Section 4, conclusions and future considerations are described.

2. Proposed Wireless Sensor Network Based Mobile Tracking System

The proposed mobile tracking system is composed of two main phases, (i) network configuration phase and (ii) real-time mobile tracking phase. There are three different node types in the proposed system: mobile target, reference or anchor node with fixed prior location information, and assistant node whose location is unknown but supports packet communications and data processing.

2.1. Network Configuration Phase

In this phase, an effective network configuration strategy is proposed to reduce the number of reference nodes required and to get the useful information for further mobile tracking phase. We set four reference nodes at the corners of the deployment area and low-cost sensor nodes with no location-aided hardware (assistant nodes) are scattered into the area of interest.

Then, connectivity information of the network is configured using the optimal RSS threshold based connectivity configuration proposed in our previous work [7] to make the proposed system robust to any network size (small to large-scale network scenarios). Each node i in the network broadcasts t packets from which each receiving node k_j (j =1, 2, ..., N_t where N_t is the total number of nodes in i's communication range) measures the RSS values. A set of RSS samples between nodes i and k_j are collected and the mean RSS value of these samples (RSS_{ij}) is computed. Then, only those pair of nodes whose RSS_{ij} value exceeds the predefined optimal RSS threshold ($RSS_{th\text{-}opt}$) is considered as connected and regarded as neighbors.

$$C_{ij} = \begin{cases} 1, \ RSS_{ij} \geq RSS_{th-opt} \ \text{(connected)} \\ 0, RSS_{ij} < RSS_{th-opt} \ \text{(not-connected)} \end{cases} \tag{1}$$

$RSS_{th\text{-}opt}$ for different number of nodes and the network size is derived using (2) [7].

$$RSS_{th-opt} = P_{ref} - 10n\log_{10} R_0 \tag{2}$$

where P_{ref} is the reference power measured at 1m, n is the pathloss exponent and R_0 is the minimum radio range required to avoid isolated nodes and to achieve a connected wireless network derived using (3).

$$R_0 = \sqrt{-\ln(1 - p^{1/N_{total}})/\phi\pi} \quad (3)$$

where p is the probability that no node in the network is isolated and φ is the node density ($\varphi = N_{total}/Area$). N_{total} is the total number of nodes in the network and *Area* is the deployment area, both of which are the prior information in most cases of practical interest of localization.

After configuration the connectivity information, regulated hop-count (*RH*) values among reference nodes and assistant nodes are estimated for further mobile tracking process. First, each reference node r_f (f=1, 2, ..., G where G is the total number of reference nodes) broadcasts a packet containing its own ID, its location and the hop-count value initialized to zero. Each intermediate node u determines whether the sender node j is its neighbor or not using the optimal RSS threshold based connectivity information. If node j is defined to be neighbor of node u (i.e. C_{uj} =1), u calculates the *RH* value between u and j (RH_{uj}) using (4).

$$RH_{uj} = d_{uj} / R_0 \quad (4)$$

where d_{uj} is the RSS-based distance between nodes u and j which is calculate based on the log-normal shadowing model equation [8],

$$d_{uj} = 10^{\frac{P_{ref} - RSS_{uj} + X_\sigma}{10n}} \quad (5)$$

where RSS_{uj} is the mean RSS value between nodes u and j obtained from the connectivity configuration stage and the shadowing factor X_σ of 0 is set. After that, u finds the *RH* value to the reference node ID in the received packet by adding RH_{uj} with the hop-count value in the packet. If the new hop-count value is larger than old value stored at u for that reference node, u simply ignores the packet. Else, old value is replaced with the new value and u forwards the packet with the new hop-count value. Through this mechanism, all assistant nodes have the minimum *RH* values to all the reference nodes which will be utilized in the real-time mobile tracking phase. As well, each reference node estimates the average size of one hop (hop-distance value) by dividing total distances to other reference nodes with total *RH* values to them, and informs it to the centralized computer. With traditional range-free schemes, if the two nodes are regarded as neighbors, distance information between them is regarded as 1-hop (i.e. size of the radio range) although their Euclidean distances are different. In contrast to this, more precise proximity information can be obtained by using the proposed regulated hop-count values. This network configuration phase has to be carried out only once while configuring the targeted area of interest for mobile tracking process.

2.2. Real-Time Mobile Tracking Phase

The proposed mobile tracking algorithm tries to locate successive movements of the mobile target by making use of the information from the surrounding static wireless sensor nodes. Before going into details of the algorithm, let us formulate some of the packet types used: (i) *RQ*: packet transmitted by the mobile target to request information from its neighbors, (ii) *RP*: packet transmitted by the neighbors of the mobile target to respond the *RQ* packet and (iii) *Loc*: packet transmitted to inform the estimated location of the mobile target to the centralized server.

2.2.1. Information aggregation

This section describes how necessary information for tracking the mobile target is aggregated. The mobile target broadcasts an *RQ* packet on each specific period ΔT ($\Delta T = T_i - T_{i-1}$ where T_i is the current tracking time and T_{i-1} is the previous tracking time). *RQ* contains packet type, mobile target's ID and T_i.

Each node n_b receiving the *RQ* packet at each tracking point (b=1, 2, ..., N_i where N_i is the total number of nodes in the radio range of mobile target at time T_i) measure the RSS value of the incoming packet. If the measured RSS value is above the optimal RSS threshold value, n_b regards the mobile target m as its neighbor and transmits *RP* packet to the mobile target m. If below the threshold, n_b ignores the request. *RP* packet contains the packet type, T_i in the corresponding *RQ* packet, mobile target ID, measured RSS value between the mobile target m and n_b (RSS_{mb}), and the *RH* values between n_b and all reference nodes (RH_{bf} where f=1, 2, ..., G) obtained from the network configuration phase.

2.2.2. Location estimation

When m receives *RP* packets, it calculates the *RH* values between it and each neighbor n_b (b=1, 2, ..., N_{i_thld} where N_{i_thld} *is* the number of $RSS_{th\text{-}opt}$ based neighbors) based on the RSS value in the *RP* packet.

$$RH_{mb} = d_{mb} / R_0 \, , \tag{6}$$

where d_{mb} is the RSS-based distance between m and n_b using (5). After that, the regulated hop-count value between the mobile target m and each reference node r_f (RH_{mf} where f=1, 2, ..., G) is calculated using (7).

$$RH_{mf} = \min(mf(b)) \tag{7}$$

$$mf(b) = RH_{mb} + RH_{bf} \text{ where } b = 1, 2, \ldots, N_{i\_thld} \tag{8}$$

Then, distance from the mobile target m to each reference node is estimated by multiplying RH_{mf} with the hop-distance value of the nearest reference node. Finally, lateration method is applied to get location information of the mobile target at T_i.

After calculating the location of the mobile target using the regulated hop-count values, the next step is to correct the estimated location using the known information of maximum velocity of the mobile target ($V_{\max}$). From $V_{\max}$, possible maximum movement ($S_{\max}$) during each sampling period ΔT can be estimated as

$$S_{\max} = V_{\max} \times \Delta T \tag{9}$$

Suppose that estimated location of the mobile target at time T_i is (x_i, y_i) and T_{i-1} is (x_{i-1}, y_{i-1}), the movement between T_i and T_{i-1} can be obtained by using (10),

$$S = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \tag{10}$$

Then, we derive the correction vector V_t using (11).

$$V_t = \begin{cases} (x_i - x_{i-1}, y_i - y_{i-1}) \times \left[\dfrac{S_{\max} - S}{S} \right] & \text{, if } (S > S_{\max}) \\ (0,0) & \text{, if } (S \le S_{\max}) \end{cases} \tag{11}$$

After that, location of the mobile target at time T_i is updated using

$$(x_i, y_i) = (x_i, y_i) - V_t. \quad (12)$$

After getting the updated location at time T_i using (12), the mobile target transmits *Loc* packet to the centralized computer which contains its estimated location. Simplified algorithm of the proposed mobile tracking algorithm is illustrated in Algorithm 1. With the proposed algorithm, the total number of packet communications required to estimate the location of mobile target at time T_i is

$$N_{pkt}(i) = 1 + N_{i\_thld} + hops \quad (13)$$

where *hops* is the number of hops *Loc* packet has to transverse to reach the centralized computer.

Algorithm 1: Proposed Mobile Tracking Algorithm

```
Information    m broadcasts RQ;                                   › m= mobile target
aggregation    for b=1 to N_i do                                  ›N_i=total number of nodes in the
               radio range of m at T_i
                   n_b receives RQ;
                   Measure RSS_mb;
                   if RSS_mb≥RSS_th-opt then
                         n_b transmits RP;
                   else
Location                 n_b ignores RQ;
estimation     m receives RP packets;
               for f=1 to G                                       ›G= total number of reference nodes
                   for b=1 to N_i_thld                            ›N_i_thld= total number of RSS_th-opt
               based neighbors
                         RH_mb ← d_mb/R_0;                        ›RH value between m and n_b
                         mf(b) ← RH_mb + RH_bf;
                   RH_mf ← min(mf);                               ›RH value between m and each
               reference node
               Estimate location using lateration;
               Update location using V_t;
               Send estimated location to the centralized computer;
```

3. Performance Evaluations

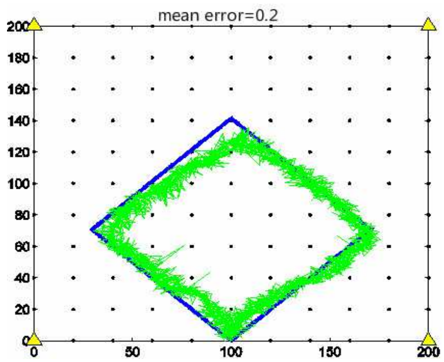
Performance of the proposed mobile tracking system is evaluated through simulations in MATLAB environment and real world experiments. The following mean error value is used as a localization accuracy evaluation function,

$$\text{mean error} = \frac{1}{N}\sum_{i=1}^{N}\left(\sqrt{(x-x_i)^2+(y-y_i)^2}\Big/R\right) \quad (14)$$

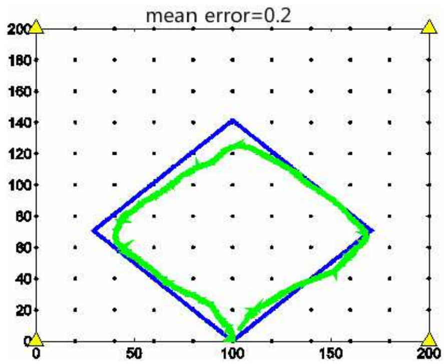
where N is the total number of tracking points, R is the radio range, (x_i, y_i) and (x, y) are the estimated location and the actual location of the mobile target at tracking point i respectively. To implement the proposed system in practice, we use XBee Series 2 modules [9] which are based on IEEE 802.15.4 ZigBee Standard to build the WSN. These modules have the ability to measure the RSS value of incoming packet without any extra hardware. Wireless modules are mounted on Arduino UNO and Arduino wireless shields.

For the mobile target, we use Bioloid obstacle detection robot [10] which has the maximum velocity (V_{max}) of 0.067ms^{-1}. Data rate of 38400 kbps, packet sizes of 20, 37 and 28 bytes for *RQ*, *RP* and *Loc* packets respectively are used in our experiments. Effective radio range (R) of XBee Series 2 modules for NLOS environment is 40m. The same parameters are utilized in the simulations to reflect the real world environment. Firstly, two sets of simulations are carried out on a 200×200m^2 large-scale area, (i) Test 1: 121 nodes grid topology network and (ii) Test 2: 121 nodes random topology network. Centralized computer is placed at the bottom right corner of the deployment areas. RSS values are modeled using the log-normal shadowing model with the radio propagation characteristics of pathloss exponent of 2.6 and standard deviation of 6.2, assuming indoor NLOS environment [7]. The movement of the mobile target is simulated to follow the square shape moving path. Speed of the node is chosen randomly between 0 and V_{max}. We use sampling frequency ΔT of 1Hz in all our simulations and experiments.

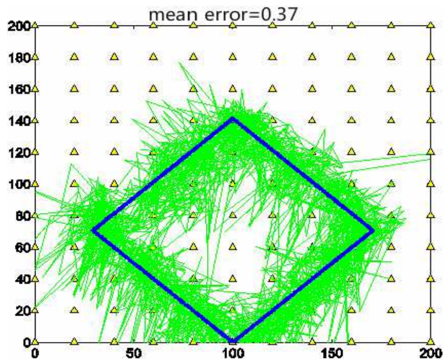
Fig. 1 and Fig. 2 illustrate the performance comparison between the proposed system and the RSS-based mobile tracking approach for Tests 1 and 2. With the proposed system, only four reference nodes denoted with triangles (Δ) are placed at the corners and assistant nodes denotes with small circles (•) are distributed inside. With the RSS-based tracking approach, all nodes in the network are assigned with the prior location information (reference nodes). Blue line represents the actual mobility path of the target and green line represents the estimated result. Results in sub-figures (a) and (b) indicate that although tracking results of the proposed system without updating with the correction vector V_t and updating with V_t give similar accuracy, the later offers smoother tracking path. Moreover, the proposed scheme shows better localization accuracy than the RSS-based approach since we effectively integrate the connectivity-based localization and the RSS ranging to minimize the RSS variability problem and to improve the accuracy. Significantly, only four reference nodes are necessary with our proposed system whereas all nodes have to be reference nodes which require additional location-aided hardware with the RSS-based approach.



(a) Proposed system (without correction).

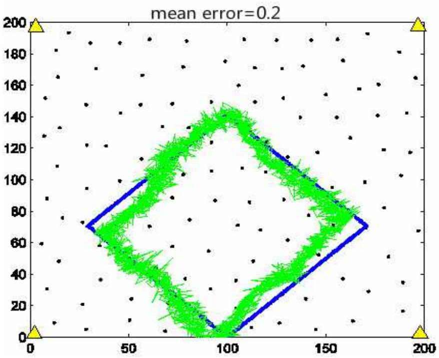


(b) Proposed system (with correction).

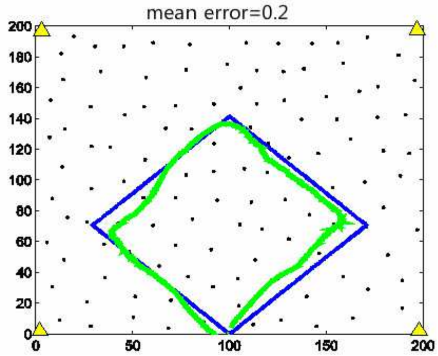


(c) RSS-based approach.

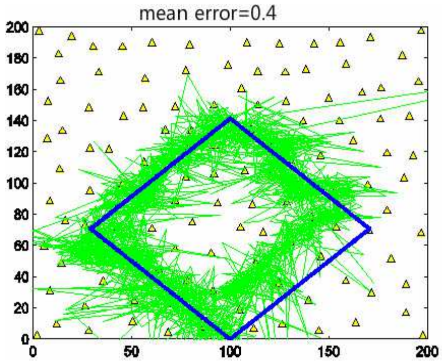
Fig. 1. Mobile tracking performance for grid topology network (Test 1).



(a) Proposed system (without correction).



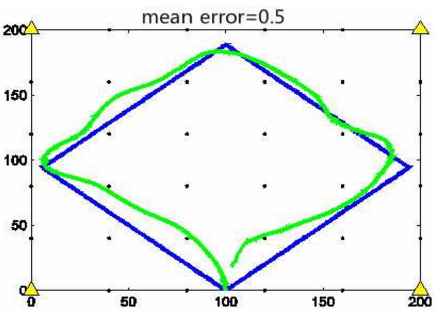
(b) Proposed system (with correction).



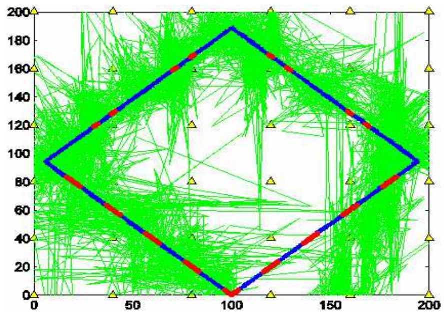
(c) RSS-based approach.

Fig. 2. Mobile tracking performance for random topology network (Test 2).

In addition, to evaluate the performance of the proposed scheme and the RSS-based tracking approach for low density network scenario, simulations are conducted on a grid topology network with 36 nodes. As shown in Fig. 3, the proposed scheme still shows preferable performance with very low density network since location of the mobile target at each tracking point can be estimated even with information from only one neighbor. But with the RSS-based approach, at some points of the actual moving path, denoted with red color in Fig. 3(b), there is no enough reference nodes for localization process (at least 3 reference nodes are required) and the mobile target cannot be tracked at those points.



(a) Proposed system.



(b) RSS-based approach.

Fig. 3. Mobile tracking performance for low density network.

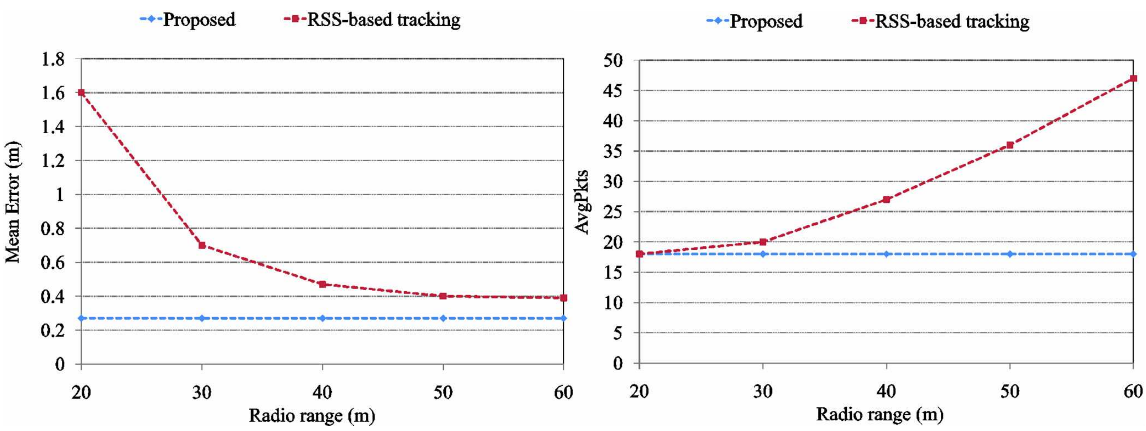
Next, communication costs of the proposed system and the RSS-based tracking method to track the location of the mobile target through a large-scale WSN are evaluated. Simulations are conducted on a 200×200m^2 random network topology with 200 nodes. Required packet communications for tracking the mobile target at T_i using the proposed scheme is calculated using (13), and the RSS-based tracking approach is calculated using (15).

$$N_{pkt}(i) = 1 + N_i + hops \tag{15}$$

Then, average communication cost is calculated using (16),

$$AvgPkts = \frac{1}{N}\sum_{i=1}^{N} N_{pkt}(i)\,. \tag{16}$$

Fig. 4 presents the tracking accuracy and the average communication cost for different radio range levels. For all radio range levels, the same tracking period is applied. Larger radio range level gives higher number of surrounding neighbors (N_i) which can receive the *RQ* packet from the mobile target at each point. Hence, the RSS-based mobile tracking approach shows higher communication cost with increasing the radio range levels. In contrast to this, changing the radio range level has no impact on the performance of the proposed system since only the nodes which are defined to be connected to the mobile target using the optimal RSS threshold based connectivity configuration participate in the tracking process for any radio range level.



(a) Accuracy (b) Communication cost

Fig. 4. Performance for different radio range levels.

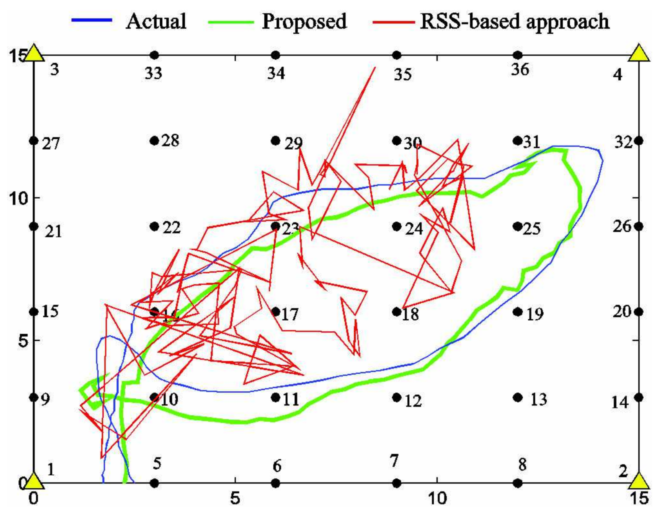


Fig. 5. Performance comparison for small-scale network.

To evaluate the performance of the proposed system on small-scale WSNs, experiments are conducted in Ritsumeikan University gymnasium. Four reference nodes are placed at the corners of the 15×15m^2 deployment area, 32 assistant nodes are distributed over the tracking area of interest and one XBee module is attached on the Bioloid robot. The centralized computer is within the radio range of the mobile target and its surrounding nodes at each tracking point since XBee Series 2 modules cover 40m radio range level even in NLOS environment. To minimize the computational overheads on the mobile target, we make some changes in the proposed mobile tracking algorithm that neighbors of the mobile target transmit *RP* packets directly to the centralized computer, without transmitting them back to the mobile target. Then, centralized computer performs the location estimation process using the received information. Results in Fig. 5 indicate that tracking performance of the RSS-based approach is largely affected by the high RSS variability in practical environment, whereas our proposed system offers preferable tracking performance.

Finally, we evaluate the localization delay (the time it takes from *RQ* packet transmission until the result is obtained at the centralized computer) of the proposed system. The localization delay (D_i) at each tracking point *i* for large-scale and small-scale networks are

$$D_i\text{ (large-scale)} = T_{rq}+A_{proc}+(N_{i\_thld}\times T_{rp})+M_{proc}+(hops\times T_{loc}) \tag{17}$$

$$D_i\text{ (small-scale)} = T_{rq}+A_{proc}+(N_{i\_thld}\times T_{rp}) \tag{18}$$

where T_{rq}, T_{rp} and T_{loc} are packet delivery time for *RQ, RP* and *Loc* packets respectively. A_{proc} is the processing time on each neighbor of the mobile target and M_{proc} is the processing time on mobile target to calculate the estimated location. We neglect the processing time on the centralized computer. Based on the experimental parameters, average D_i for tracking the mobile target through the small-scale network shown in Fig. 5 is 0.09 s. It means that estimated location of the mobile target at sampling time T_i is displayed at the centralized computer after the mobile target has already moved by 0.006 m. A larger localization delay will be resulted with multi-hop large-scale networks since *Loc* packet has to transverse several hops to reach the centralized computer. To minimize the localization delay, wireless modules with higher processing capability micro-controllers should be utilized for tracking through large-scale networks.

4. Conclusions

In this paper, we propose an efficient WSN-based mobile tracking system which not only improves the localization accuracy but also reduces the extra hardware requirement by integrating the connectivity-based range-free and the RSS-based ranging approaches. The mobile target is tracked based on the regulated hop-counts values and the available RSS measurements from the surrounding nodes, instead of using the known location information of them, to minimize the reference node utilization. Additionally, known information of the maximum velocity of the mobile target is effectively applied to improve the performance of the proposed tracking algorithm. Results show that the proposed system shows preferable tracking performance in both small and large-scale networks with different node densities. Multiple mobile targets can be tracked using the proposed system, but considerations of reducing communication overheads due to multiple targets will be future extension to our current work. Proposed system can be deployed in many applications like tracking rescuers or victims in case of disaster relief and tracking employees in workspace.

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