A Localization and Position Tracking Solution Utilizing Solar-Powered RFID Tags

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Abstract— **The ability to determine the position of a device in outdoor or indoor environments is becoming the foundation for an ever increasing number of a diverse set of services. This paper demonstrates the implementation of a very low-cost localization and device tracking system on top of a Wireless Sensor Network (WSN) topology. Its major components, namely the mobile RFID prototype, the fixed wireless infrastructure and the central server, are described and an initial evaluation of the accuracy of the system is presented.**

I. INTRODUCTION

Localization is the process of determining the physical position of a user or a device with a particular degree of accuracy in indoor or outdoor wireless sensor network fields. The physical location information of a node can be a very useful or even indispensable functionality in a large number of applications, such as device tracking, involving location and bearing, geographic aware routing protocols and context-aware ubiquitous applications.

The goal of the work presented in this paper is the provision of location information regarding a solar powered battery-less RFID tag hung from the front mirror of a vehicle in large scale parking lots to customers, such as car auction dealers. The localization technique deployed is the Received Signal Strength Indicator (RSSI)-based lateration.

II. LOCALIZATION TECHNIQUE: LATERATION

The, mostly, static nodes, whose exact location coordinates are known a priori, are called anchor nodes. The approach according to which distances from three (trilateration) or more are used to estimate a node's unknown location is called lateration. The estimated position is given either relative to these anchors or to absolute coordinates, provided that the absolute coordinates of the anchor positions are known. The received signal strength indicator (RSSI) returned by the anchor's transceiver after the reception of a packet from another node can serve as an estimate of the physical distance between them. In particular, the distance from the emitter can be estimated by plugging this RSSI value along with the known effective isotropically radiated power (EIRP), which takes into account the transmission power, the antenna gain and the cables losses of the emitter, into the Friis equation for a particular path loss coefficient and model. The applied latter model, of course, can be very sophisticated depending on the surrounding environment.

For the lateration to be deployed, neither additional hardware nor additional communication overhead is required.

However, there are a few parameters that can degrade the accuracy of the RSSI approach. First, a number of broadcasted packets might have followed an indirect path due to multipath fading, regardless of whether they have been emitted from an anchor node in line-of-sight with the receiver or not, in which case the RSSI extracted introduces incorrect estimations. Second, the fast-fading effect, as well as the dynamic nature of the environment, can result in serious oscillations in the RSSI measurements over time. Additionally, the actual transmission power can differ from the configured one and the measured RSSI value might not correspond precisely to the actual received signal strength, since the widely used inexpensive radio transceivers are in most cases not calibrated [1]. This latter problem, however, can be entirely eliminated by individually calibrating all nodes' transceivers. In the framework of this work, efforts, described in Section IIIC, have been made to alleviate the above degrading effects before the trilateration is conducted.

III. THE OVERALL SYSTEM / SOLUTION

The three major components that comprise the overall system, specifically the mobile RFID prototype, the fixed wireless infrastructure and the central server, have been designed to interoperate as more efficiently as possible. These are described in the following subsections.

A. The mobile RFID prototype

The main functionality of the microcontroller (MCU)-enabled RFID prototype, shown in Fig. 1, is the wireless transmission of identical, unique identification packets in regular intervals triggered and powered using energy present in ambient sunlight without a conventional battery. As expected, the parameters governing the performance of the tag are the effective isotropic radiated power, the total transmit time and the time interval between adjacent transmits.

This tag utilizes super capacitors, which are much cleaner to dispose environmentally and have much higher recharge lifetimes than batteries. These are charged by the unlimited and clean solar energy harvested by a parallel configuration of solar cells interfacing to the tag through a power management circuit (PMU), which is in turn interfaced to the integrated 8-bit microcontroller unit (MCU) housed in the same chip as the RF transmitter. The MCU transits from "on" to "sleep" mode and vice versa with the help of the PMU based on the amount of the solar energy collected across the charge tank capacitors. The power management unit is comprised of discrete analog
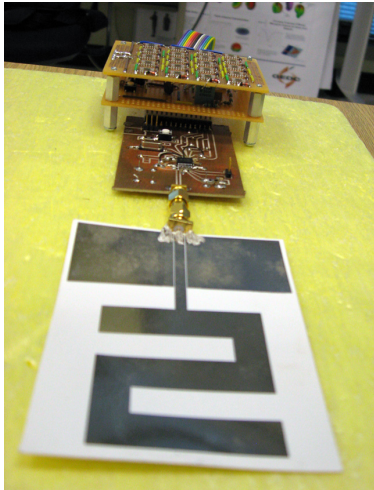
Fig. 1. The mobile RFID prototype.

circuitry. The microcontroller firmware ensured that the tag identification was transmitted using the same RF power irrespective of the external light conditions, thereby ensuring that the EIRP from the tag remains the same within the area, where it is being tracked.

The radiated power has to be omni-directional for the purpose of an accurate localization computation. Omni-directionality was achieved by ensuring an antenna gain close to 0dB. The proposed monopole antenna design [2] was fabricated on paper using inkjet-printed technology in-house and is shown as part of the working prototype in Fig. 1. The antenna was tweaked to ensure that its impedance was equal to 36.95-j71.77Ω, which is the conjugate of the optimum load impedance of the amplifier in the wireless transmitter of the tag prototype. This ensures that the almost the whole amount of the solar power harnessed is radiated out from the amplifier into the antenna as RF power.

B. The fixed wireless infrastructure

The key decision that has enabled the cost of the proposed localization solution to be drastically low is the deployment of a Wireless Sensor Network (WSN) as the backbone infrastructure, instead of RFID readers which are not only much larger in size dimensions than typical WSN motes but also two orders of magnitude more expensive, and the successful establishment of an asynchronous communication link between a WSN node and the RFID tag presented in the previous section. The motes consisting the WSN are the Crossbow's MICA2 [3]; one of the most widely used as of the time of this writing.

For the WSN infrastructure to be able to capture packets transmitted by the RFID tags, to extract the unique mote id and received signal strength indicator in dBm scale and to

timestamp them based on a network globally synchronized time before forwarding them to a central server, both anchor and end nodes are required to "follow" the same protocol. Regarding the physical layer, first the transmission has to be carried out over a frequency channel supported by both sides, which in this case is 904.4 MHz, and second the transmitted signal has to be Frequency Shift Keying (FSK) modulated meeting specific frequency and modulation requirements. In regards with the link layer, the WSN mote is expecting the packet to be properly encapsulated before extracting the payload, which is the actual information carried. This "overhead" is not only used for communication protocol purposes but can provide topology-related knowledge and error handling functionality. More specifically, the format of the packet sent from the tag, which is received by the WSN node's TI CC1000 transceiver [4], consists of the following fields: Preamble, Sync, Addr, Type, Group, Length, Payload, and cyclic redundancy check (CRC). The first two fields are used for the synchronization of the receiver's clock and the latter field, CRC, helps determine if a packet is corrupted or not and discard it if needed. The Payload, of course, conveyed the unique identifier of the tag.

C. The Central Server

After the successful reception by each WSN anchor node of the beacon message broadcasted by an RFID tag, significant information, namely RSSI, unique tower id and time stamp, is appended to the packet and the latter is forwarded to the central server through either XMesh [5] multihop protocol or over an overlayed IEEE 802.11 WiFi network. All these message entries are imported at the central location into a Sqlite database.
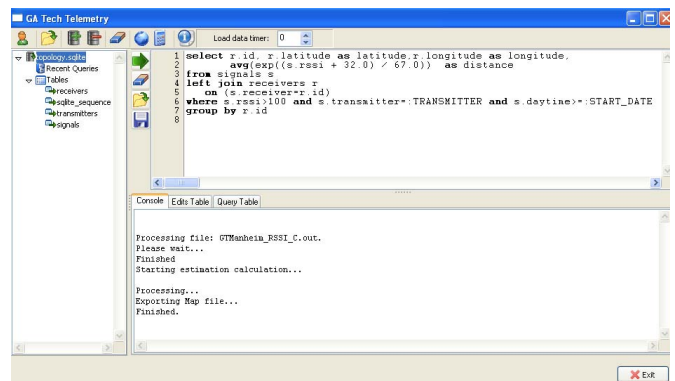

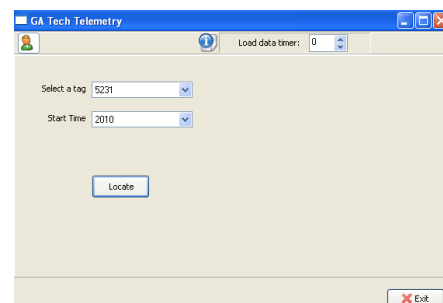Fig. 2. The central server's configuration mode.

Fig. 3. The central server's user mode.

Data validity checks are the first type of process performed to the message entries, i.e. a number of filters are applied to reject invalid entries due to, mainly, bit errors introduced. Then the RSSI data, after it is filtered for bit sequence inconsistencies, is extracted and passed through Kalman filtering with the use of appropriate procedure language R functions in order to remove any signal noise present. Moreover, the transceiver calibration issues discussed in Section II are encountered with the conductance of separate test measurements right after the deployment of the anchor nodes. Specifically, RSSI values recorded at fine grained set distances from an anchor node and for known transmit power are rigorously mapped for different field wireless propagation profiles; for example, for different percentages of occupation of the parking lot by vehicles. The time-stamp information availability enables the use of a timer function, which loads data from specific time periods in the past relative to the time the location estimate was initiated.

Since the localization solution is based on the RSSI lateration technique, the filtered RSSI data is used for the distance estimation between the tag and a particular WSN node with the use of either a free path or a two-ray tracing radio propagation loss model. Finally, the trilateration is performed as a database procedure call [6] and in turn functions are called to display the returned WGS 84 latitude-longitude coordinates on Google Earth [7].

A screen-shot of the graphical user interface of configuration mode of the computer program created is shown in Fig. 2. In the left column shown, the user can configure the absolute coordinates of the anchor nodes under "receivers", the unique IDs of the tags under "transmitters", whose location is to be estimated, and all the message entries captured by the anchor nodes are collected under the "signals". The query that both performs a simple filtering of the data and applies the radio propagation model chosen is shown in the upper right box. All status update messages are shown in the lower right box. After the one time configuration is performed, the user can revert to the simplified user mode of the program, shown in Fig. 3.

IV. EXPERIMENTAL RESULTS

In order to verify the feasibility of this proposed solution for localization and position tracking applications, actual measurements of the location estimate errors were taken at different positions of the tag in two different real-world fields, covered by a number of WSN fixed anchor nodes. This location estimate error is equivalent to the Euclidean distance between the estimated absolute coordinates returned by the program and the coordinates of the actual position of the RFID tag. The first one was the rooftop of the Georgia Tech hotel's parking deck and the second one was a large car auction dealer's parking lot in Southern Atlanta.

Both WSN topologies were designed to allow the WSN anchor nodes, which were mounted on lamp posts, to better receive the transmitted data by the tag, which would result in better localization estimates. The tag was hung from the rear mirror of a vehicle that was driven around at different

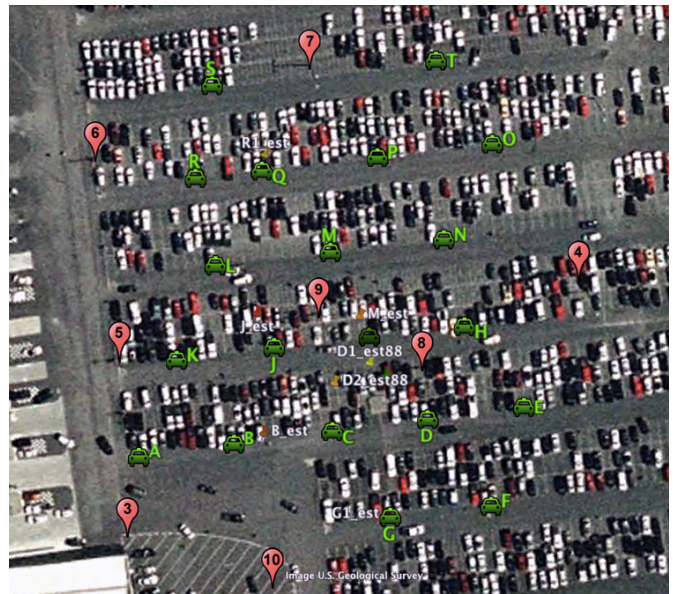Fig. 4. The Georgia Tech hotel's parking deck rooftop

Fig. 5. A large parking lot.

positions of the fields to verify and benchmark the returned location estimations. From the radio propagation perspective, it should be noted that the requirement for the clearance of at least the 80% of the first Fresnel zone was satisfied [8] for most positions for the anchor nodes that were in line of sight from the vehicle's windscreen. For both test bed setups, where the average height of the motes above the ground was 3.5m and the height of the tag was around 1.5m, the value of the radius of the cross section of the ellipsoidal of the first Fresnel zone at the middle of the distance, typically 75m, was approximately 2.8m and the same value just 0.5m away from the mote side was around 0.3m.

A. A hotel's parking deck rooftop

The satellite image of the 80m by 80m area of the empty rooftop of the Georgia Tech Hotel parking deck is shown in Fig. 4. Six WSN anchor nodes are mounted, as described

previously, on existing lamp posts that are denoted with increasing numbers 3 through 8; four of them are placed on the periphery of the topology and two of them around the center.

Two localization estimate examples returned in Google Earth, namely hhr-estA and hh-estC, are pinpointed in Fig. 4 and can be compared to their respective real position, denoted with the car icons A and B, respectively.

B. A large parking lot

The WSN topology consists, in this case, of 8 anchor nodes, denoted by the red pins numbered 3 through 10 in Fig. 5. The diameter of the area covered by the overall topology is around 190 m, and the radius of the area covered by each anchor node is roughly 90 m. Consequently, the percentage of the overlapping areas within the overall field is high, as desired.

The green car icons correspond to predetermined positions from which an attempt to estimate their location was made so as to get an initial evaluation of the performance of the localization system. Five such examples, namely D1, D2, J, M and R1, are shown in Fig. 5.

V. Conclusions

The need for truly cognitive location intelligence over extended physical distances on top of very low-cost and mature wireless infrastructures is ever increasing. Toward this goal, a localization and device tracking system that can be implemented very easily and with low cost on existing WSN topologies has been presented.

As a representative example to better assess the benefits provided by such a localization service, the user of the demonstrated solution in car auction premises, is enabled not only to directly locate any vehicle fast and accurately, but can also to exploit the location data for optimization and cost reduction of the lot's everyday operations.

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