Cortina: Collaborative Indoor Positioning Using Low-Power Sensor Networks

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***Abstract*—Cortina is a distributed *Real-Time Location System* (RTLS) designed to track assets or people moving indoors. Our solution leverages a low-cost, low-power *Wireless Sensor Network* (WSN) based on the IEEE 802.15.4 radio standard. The network, which consists of wall-plugged sensor nodes, is designed to be self-configuring, self-healing and self-calibrating, thus reducing deployment and maintenance costs. Assets and people are tracked using small battery operated wireless tags that collect Received Signal Strength (RSS) measurements from nearby sensor nodes. The tags also include an accelerometer for activity recognition, and a barometric pressure sensor to accurately detect the floor plan. We have conducted experiments over a $2000\,\mathrm{m}^2$ area instrumented with eighteen sensor nodes. Our initial results show that the system can track people in real-time with an average error of $2.8\,\mathrm{m}$.**

Keywords: Indoor Positioning, Wireless Sensor Network, RFID, RSS, Self-Calibration, Trilateration, RSS map.

I. Introduction

In the past few years, indoor positioning has received a great deal of attention both from the research community and the industry [4], [5]. Several solutions are available to enable location awareness in environments with insufficient GPS reception. For example, applications demanding high accuracy can leverage *Ultra-Wide Band* (UWB) systems based on *Time Difference of Arrival* (TDoA). Lower cost applications can be supported by *Real-Time Location Systems* (RTLS) based on existing infrastructure such as WLANs and cellular networks. Previous research has demonstrated that these solutions can locate users with low error, typically two to three meters, when the systems are calibrated by collecting *fingerprinting* data (e.g. [3], [6]).

Cortina is an indoor RTLS that exploits an inexpensive sensor network in the attempt to further optimize the trade-off between performance and cost. The aim of this work is to describe our system and outline technical details that can facilitate implementation of other future RTLS's.

II. Design Principles And System Architecture

In designing Cortina we have strived to create an RTLS that is 1) **low-cost**, 2) **easy to deploy**, and 3) **accurate**. These design goals are achieved by leveraging the *Wireless Sensor Network* (WSN), a new computing paradigm that has gained popularity in the past years and already counts many applications in civilian and military domains [2].

A WSN consists of a group of low-cost radio devices enabled with sensors and/or actuators. These units are capable of organizing themselves into an ad-hoc, multi-hop wireless network that enables data collection and dissemination. In Cortina, the WSN is used to create the fixed infrastructure of our RTLS. More specifically, the WSN is formed by small and inexpensive wireless sensor nodes designed to be plugged in the available power outlets (see Fig. 1). These sensor nodes, which are compliant with the IEEE 802.15.4 radio standard, are programmed to automatically create a mesh network. Units can be added or removed at any time without requiring manual configuration from the user.

The WSN infrastructure interacts with small battery-powered *Wireless Tags* (WTAGs) that can be worn by people or attached to asset (see Fig. 2). When a WTAG arrives in proximity of the Cortina WSN, it starts measuring the *Received Signal Strength* (RSS) of beacons transmitted by the fixed nodes. The RSS values are transmitted back to the WSN and then forwarded to a central server that estimates the WTAG's position. Figure 3 shows a block diagram of the system architecture and its building blocks.

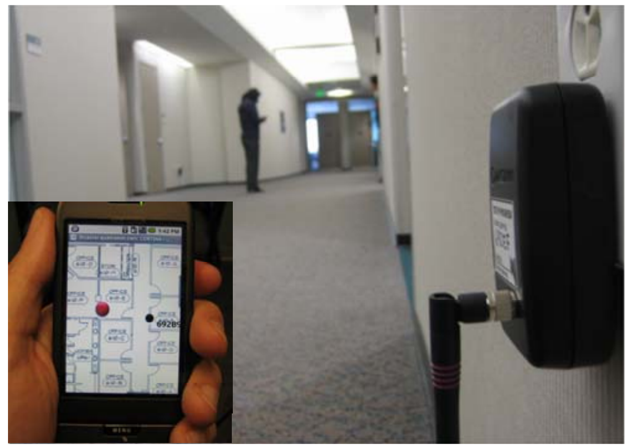

Fig. 1. On the right, one of the wall-plugged nodes of the Cortina positioning system. On the left, a web page that displays real-time position of the user.

Fig. 2. Examples of WTAG worn in different positions.

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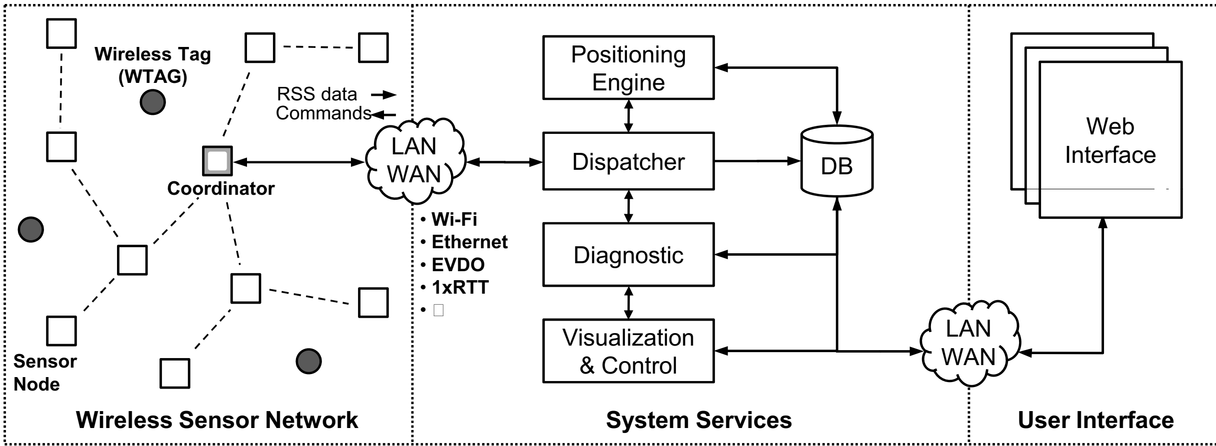

Fig. 3. Architecture of the Cortina system.

III. Overview of Novel Solutions

The Cortina RTLS exploit a sensor network to implement an infrastructure that is both inexpensive and easy to maintain. In addition to the WSN, we have implemented many custom solutions aiming at further reducing the deployment costs and improving performance. In the following sections we provide an high level overview of some of the features and implementation choices for the hardware, the firmware, and the positioning algorithms.

A. Sensor Nodes

The sensor node's design is centered around the Jennic JN5139 [1], a module that features a $2.45\,\mathrm{GHz}$ transceiver compatible with the IEEE 802.15.4 standard. The nodes (see Fig 4-left) use this radio to communicate with other units and the WTAGs. Eventually the data generated within the network are routed to a central server by the *coordinator*, a special node equipped with an Ethernet interface (see Fig. 4-center). All nodes implement features that facilitate indoor deployment.

*1) **High Power Radios**:* Since sensor nodes are plugged into power outlets, we have chosen the high power version of the JN5139 module. With an output power of $19\,\mathrm{dBm}$ and a receiver sensitivity of $-100\,\mathrm{dBm}$, this radio can provide coverage up to 4 kilometers in open space. Indoors we have successfully established communication between nodes with distances in excess of 70 meters. The use of radios with high link budget ensures reliable communications over large areas. In addition, high power transmissions increment the number of beacons received by each WTAGs. Since these messages are used to compute the tag's location, an higher number of message improves the localization results.

*2) **RFID for Sensor Self-Positioning**:* At any given time, the system needs to know the location of the fixed nodes. To simplify deploy and maintenance, each sensor node is equipped with a *Near Field Communication* (NFC) chip capable of reading standard RFID tags. Before deploying the Cortina WSN, we have attached RFID tags on the power outlets in our building and recorded their physical locations in a database table. This is a one-time operation that can be performed before deploying the system, or, ideally, carried out at the time the edifice is built.

Every time one of the sensors is plugged into a power outlet, the RFID code read by the NFC chip is transmitted to the central server and resolved into a location. Eliminating the need to manually maintain the node locations has proven effective in reducing deployment efforts and also avoid system malfunctioning due to misplaced nodes. The RFID-based scheme enables true plug-n-play operations, allowing the system to be maintained by non-skilled personnel.

B. Wireless Tags

The WTAG shares some of the same electronics used on the sensors (see Fig. 4-right), but the components have been chosen to reduce size and power consumption. The WTAG features the standard version of the JN5139, a module that consumes about $37\,\mathrm{mA}$ when in RX/TX mode, and just $2.6\,\mu\mathrm{A}$ when in sleep mode. The use of a low-power radio makes it possible to extend the battery lifetime, which is a critical factor to reduce maintenance costs when tags are used for asset tracking. In addition to the use of low power radios, each WTAG is augmented with a Bosch BMP085 barometric pressure sensor and a Bosh BMA150 three-axis accelerometer.

*1) **Use of Pressure Readings for Floor Detection**:* The pressure sensors mounted on the WTAGs were included to improve 3D localization when tracking targets in multi-floor buildings. While many applications can tolerate errors of a few meters in the horizontal plane, similar errors along the vertical dimension can position a target in the wrong floor. Barometric pressure readings represent a viable solution to reduce the occurrence of this type of error. Figure 5 shows the output of the Bosh BMP085 sensor when riding the elevator from the sixth floor to the basement.

The data in Fig. 5 suggest that accurate floor detection is possible using barometric pressure measurements. Some of the fixed sensor nodes are equipped with the same sensors and provides baseline values. These values are use to compensate for variation in pressure due to different weather conditions.

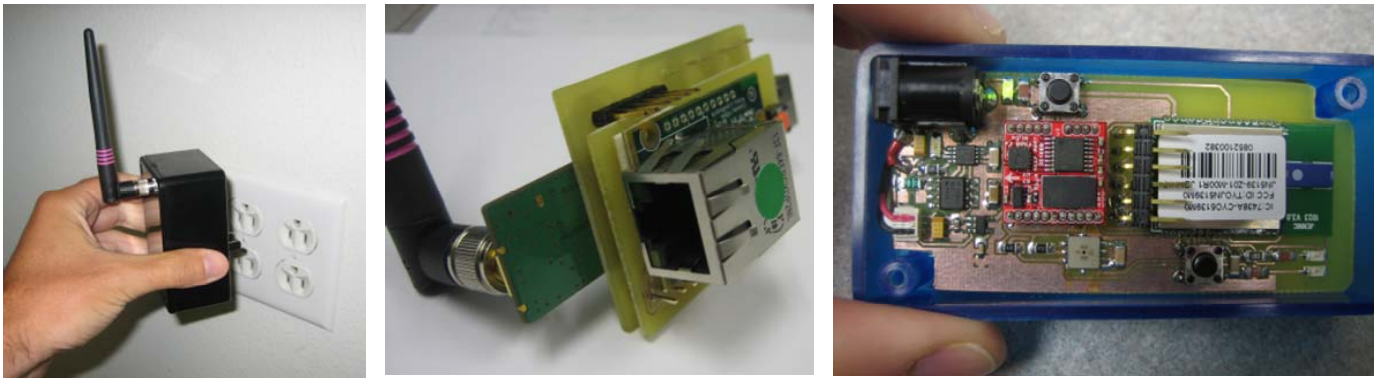

Fig. 4. left) One of our sensor nodes plugged into a power outlet; center) a detail of the Ethernet module used on the coordinator to support LAN connectivity; right) one of our wireless tags (WTAG)

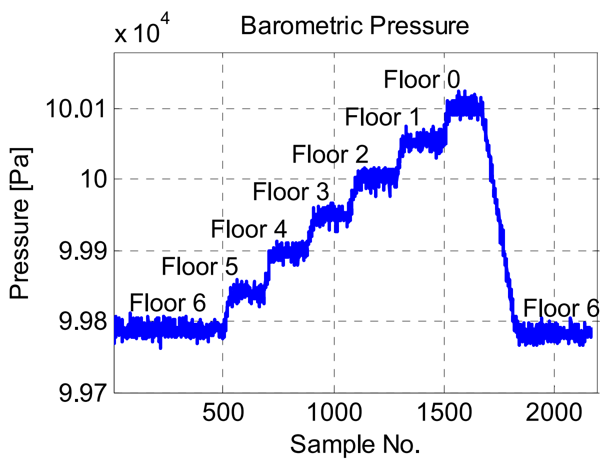

Fig. 5. Barometric pressure readings collected when riding the elevator from the sixth floor of QRC to the basement. On the way down, the elevator was briefly stopped on each floor.

*2) **Activity Recognition**:* The readings from the three-axis accelerometer are processed in real-time by an activtiy recognition module running on the WTAG. The firmware recognizes four main activities: *i) Motionless, ii) Fidgeting, iii) Walking, and iv) Running*. The code for data processing, feature extraction, and activity classification is executed on the WTAG without requiring external communications.

The ability to detect the WTAG's activity is beneficial for three reasons. First, power consumption can be optimized by adjusting the duty cycle of the tag: The frequency of the location updates can be increased when movement is detected, and reduced to a minimum when the tag is stationary. Second, if the tag remains stationary, it is possible to average the measurements collected over longer periods of time to improve the location accuracy. This is particularly important to exactly pinpoint the location of static WTAGs that might be located in some remote area of a building. Finally, activity data provide valuable information when monitoring people, especially children or elderly.

C. Positioning Algorithms

Cortina implements an RSS-based positioning system that is attractive because it only requires simple hardware, both on the fixed and mobile nodes. As discussed in the previous sections, simple *beaconing* from the sensors is sufficient to collect the RSS data used to localize the WTAGs. The RSS values are converted into position estimates using two different algorithms: the first one is based on trilateration; the second one uses RSS maps. Here we outline some of the solutions used to improve the results of both algorithms.

*1) **Automatic Algorithm Calibration**:* Since signal propagation varies widely from building to building, many RTLS's leverage fingerprint models that are periodically recalibrated by measuring the RSS at known locations [4].

Cortina avoids the need for manual calibration by adopting a collaborative approach that uses RSS measurements collected by the fixed nodes. Each node continuously monitors the RSS of the messages transmitted by the other nodes and periodically transmits aggregate statistical values to the server. For the trilateration algorithm, the RSS values are used to update the coefficients of a polynomial regression model that relates signal strength to distance. For the RSS map approach, the RSS values are linearly interpolated to create 2D maps of the signal strength in the building. The maps are then used by algorithm similar to a fingerprinting scheme.

The collaborative approach not only alleviates the deployment cost, but also makes the system more robust to changes in the environment. For example, people moving in and out of conference rooms, or relocation of big pieces of equipment, causes significant fluctuations in the RSS that are automatically taken into account by the recalibration process.

*2) **Accounting For Unknown Receiver Gain**:* The positioning algorithms are also designed to compensate for the variability in RSS caused by transceivers with uncalibrated output power and different antenna gains. In particular, the propagation model is calibrated using measurements among sensor nodes that share the same type of transceiver and the same type of antenna. The RSS measured by the WTAGs are always attenuated due to the reduced antenna dimension and different polarization. In our experiments, we have measured

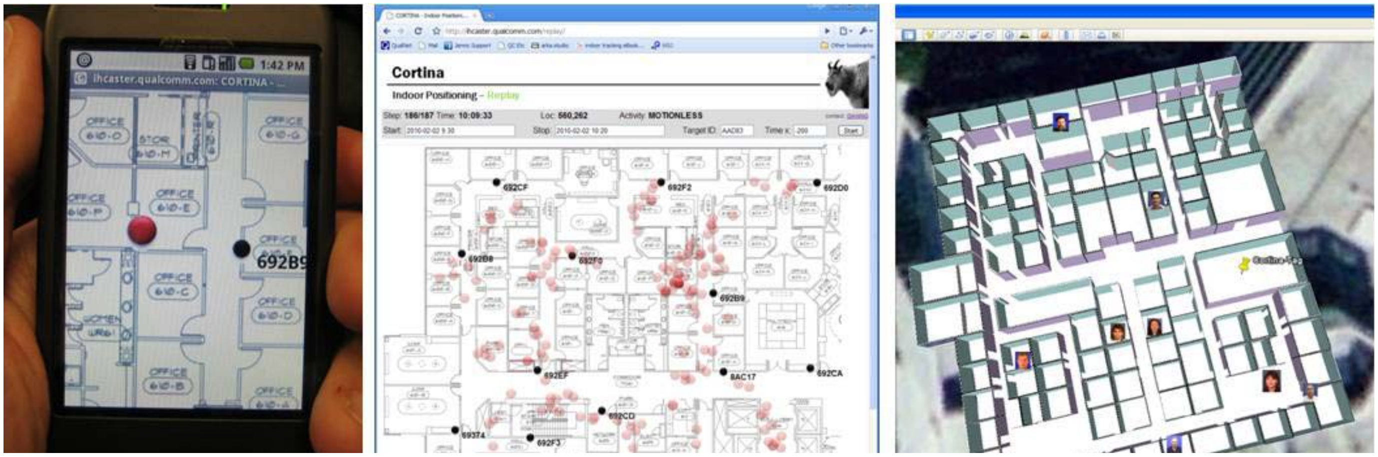

Fig. 6. left) AJAX web page that displays real-time information about the position of a target - the page can be accessed using a computer or a smart phone; center) web page that displays location traces over a period of time; right) Google Earth real-time visualization of the target's position.

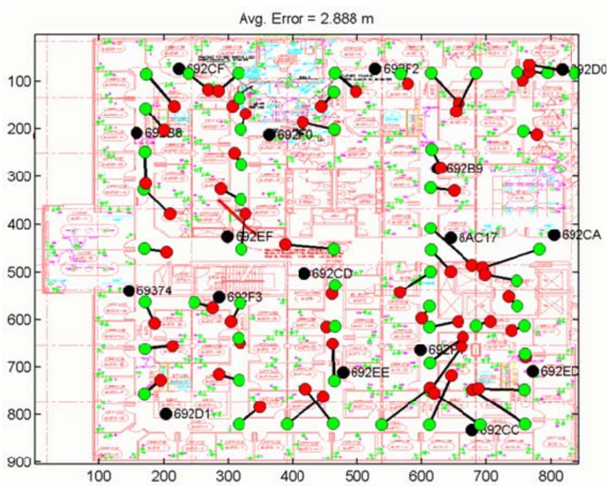

Fig. 7. Tracking error for a target moving on the sixth floor of the QRC building. The green dots are the true target positions, the red dots are the position estimates. The black dots represent the fixed nodes.

an attenuation of approximately 20 to 30 dBm when the WTAG is used to measure the RSS. The two algorithm implemented in Cortina are both designed to leverage the RSS collected from multiple sensor nodes and compensate for the receiver gain. In the trilateration approach, all the distance estimates are treated as arbitrarily biased *pseudo-ranges*. In the RSS map scheme, the values used in the computation are differential readings between pairs of nodes, thus eliminating the effect of unknown gains. These solutions not only enable effective tracking of etherogeneous wireless devices, but also mitigate the error due to the human body attenuation.

IV. Results

As part of our research, we have deployed 18 nodes over an office area measuring approximately 2000 m^2. The Cortina RTLS has been running continuously for more than 14 months, tracking in real time the location of about ten volunteers who offered to wear the one of the WTAGs.

In one of our tests, we marked 56 locations on the sixth floor of our building. One of our collaborator moved from point to point wearing one of the WTAGs. Figure 7 shows the results of such test. The green dots are the true locations, while the red dots are the positions estimated by averaging the output of the trilateration and RSS map schemes. The error in this controlled test is comprised between 0.38 and $5.95\,\mathrm{m}$, with an average error equal to $2.88\,\mathrm{m}$. In eighty percent of the cases, the error is below $4.25\,\mathrm{m}$.

More in general, our tests have shown the soundness of the WSN approach in designing a self-configuring, self-calibrating RTLS capable of tracking people and assets with an average error of approximately two to three meters. This level of accuracy is sufficient to correctly detect the room or the corridor where the target is moving without requiring filtering algorithms. During our tests with the system we particularly appreciate the simplicity of deployment and maintenance. The RFID-enabled, wall-plugged sensors make it easy to extend the network or replace defective units. The ability to plug additional sensor nodes is also important to improve the accuracy of the system. Some of our latest research directions within the Cortina project are described in [**?**].

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