RF-based Device-Free Localization and Tracking for Ambient Assisted Living

M. Bocca[1], S. Gupta[2], O. Kaltiokallio[3], B. Mager[1], Q. Tate[1], S. Kasera[2], N. Patwari[1], S. Venkatasubramanian[2]

[1]*Electrical and Computer Engineering Department, University of Utah, Salt Lake City, USA*
[2]*School of Computing, University of Utah, Salt Lake City, USA*
[3]*Aalto University School of Electrical Engineering, Helsinki, Finland*

Abstract – Radio frequency (RF) sensor networks are wireless sensor networks (WSNs) which use only the received signal strength (RSS) to perform tasks such as device-free localization (DFL) and tracking of individuals. In these systems, people to be located do not participate in the localization effort by carrying any radio device or sensor. Instead, a static deployed wireless network measures RSS on its links and locates people based on the variations caused by the movements of people in the monitored area. In this paper, we present features and functioning of an RF sensor network deployed in a home for indoor localization and tracking for ambient assisted living (AAL). Our system is composed of low-power IEEE 802.15.4 transceivers, operating in the 2.4 GHz ISM band, that collect and process RSS data in real-time and estimate the locations of people over time.

1. Introduction

Radio frequency (RF) sensor networks for device-free localization (DFL) and tracking can be effectively used in several application domains [1], including ambient assisted living (AAL). In these systems, people to be located are not carrying any radio device or sensor to participate in the localization effort, thus making this technology less invasive compared to those in which people must wear a device. Gerontology experts believe it is important to use passive, rather than wearable, sensors when monitoring an elderly population [11]. In order to perform the localization task, a static deployed RF sensor network exploits the motion-induced variation of the received signal strength (RSS) of wireless links to locate and track moving people in the area.

RF sensor networks use commercially available low-power IEEE 802.15.4 transceivers, operating in the 2.4 GHz ISM band, to collect RSS measurements. These nodes have been used in several DFL systems, and different data processing methods have been proposed, providing high localization accuracy indoors, through walls, and in noisy and obstructed environments [3] [4] [5]. In this paper, we present the main features and functioning of our DFL system for AAL applications.

2. System architecture

2.1 Hardware

The nodes we use in our DFL system are the Texas Instruments' CC2531 USB dongles, which have an IEEE 802.15.4 radio with a transmit power of up to 4.5 dBm [6]. The nodes have a on-board printed inverted-F antenna, and can be powered either by two standard AA batteries or through a USB power adapter plugged into a wall socket. The battery packs offer flexibility in setting up an array of nodes, while the power adapter option allows for keeping the nodes active for an indefinite amount of time. One node is used as a gateway and transfers RSS measurements from the network to a laptop via USB port, which are then processed on the laptop.

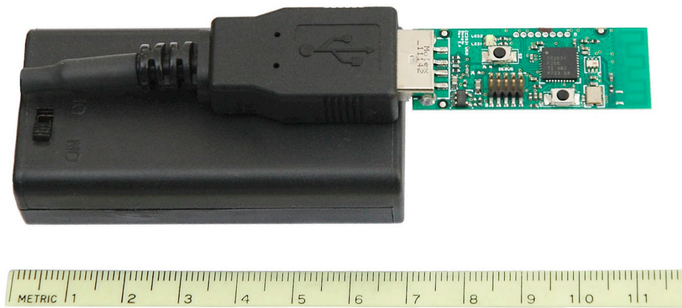

Figure 1. A CC2531 USB dongle node with battery pack (11.2 x 3.3 x 3.0 cm)

2.2 Deployment

In the *Living Lab* deployment, some nodes are plugged in the wall sockets, wherever that option is available. Other nodes, powered by batteries, are fixed to other locations (for example on walls, under tables, on furniture, etc.) by means of adhesive tape. The nodes are positioned at a height from the floor varying from 0.5 to 1.5 m. In this way, the wireless links between each pair of nodes have sufficient density through all parts of the home, and intercept the upper part of the human body, which causes the most significant attenuation of the radio signal. The total number of deployed nodes depends on the configuration of the monitored area and on the number and size of the obstructions found in it. As observed in our previous tests [3] [10], in order to guarantee sub-meter localization and tracking accuracy, our system needs to have nodes deployed along all the sides of the monitored environment, with neighboring nodes separated by up to 2 m.

2.3 Communication protocol

The nodes composing the DFL system communicate in a TDMA protocol, with slot based on their ID number. Each node transmits a broadcast packet to all other nodes, and any transceiver in range measures its RSS. This mesh network measurement architecture provides a higher density of wireless links than a star architecture. The nodes receiving the packets record the RSS and save the measurement in an array, which is then transmitted in their next packet. In this way, the gateway node receives all the RSS measurements from all the links in the network. The packets transmitted by the nodes are time-stamped upon reception at the gateway by using a high-resolution hardware timer. The reception of a packet is also used by the nodes to calculate the time they need to back-off and wait before broadcasting their next packet. In our current tests, carried out with a network composed of 26 nodes and a gateway, the total cycle time is 68.6 ms.

The communication protocol we currently use may function using either a single, or multiple, 802.15.4 channels. In the latter case, at the end of each cycle of transmissions, all nodes (including the gateway) simultaneously switch their frequency channel to the next channel in a list of channels previously defined by the user. Measuring RSS at different center frequencies provides greater insight into the characteristics of the radio propagation environment, enabling localization to be more robust to fading and interference [10].

2.4 Position estimation

Several techniques for localizing objects, *i.e.* people, in an area surrounded by communicating wireless nodes have already been proposed [3] [4] [7]. These methods assume that the position of the nodes is known a priori and that human motion induces variation of the links' RSS measurements. By knowing

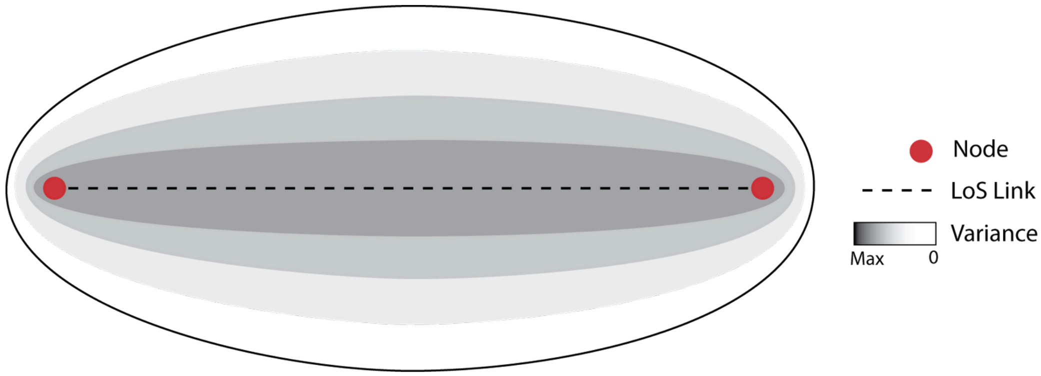

Figure 2. The ellipsoidal model of a link's RSS variance

how objects affect the radio signals' propagation patterns [8], it is possible to localize and track moving individuals in real-time.

In [3], the area in which motion affects links' RSS variance is modeled as an ellipsoid having foci at the transmitting and receiving node locations. Motion occurring in the area covered by this ellipsoid increases the link's variance. Also, according to the model, as the link gets longer, the RSS variance caused by human motion becomes smaller. By combining the variance measured by all the links of the network, it is possible to create an image vector **x** describing the presence of motion occurring within the spatial voxels of the network area. A linear model relating motion in space to a link's RSS variance can be expressed as:

$$\mathbf{s} = \mathbf{W}\mathbf{x} + \mathbf{n}, \quad (1)$$

where **s** is a vector of RSS variance measurements, **W** is an M (i.e. number of links) x N (i.e. number of voxels of the motion image) matrix, and **n** is an M x 1 noise vector. In our system, RSS measurements are collected at a constant interval T_s, corresponding to the transmission interval of the nodes. The RSS variance of each link is estimated from the most recent N_b RSS samples (e.g. N_b = 5). A Tikhonov-regularized least-squares estimator estimates **x**. A Kalman filter is applied on the reconstructed motion image to reduce its noise and increase the tracking smoothness.

In addition to the variance-based version of radio tomographic imaging (VRTI), which will be used to localize and track moving individuals, our DFL system will exploit kernel-based radio tomographic imaging (KRTI) [9], which is also capable of localizing stationary people. In this method, the system forms and updates in real-time for each link l a long-term (q_l) and short-term (p_l) histogram of RSS measurements for each link of the network. A kernel function is then applied to calculate the distance of the short-term histogram from the long-term one as:

$$d_l = p_l^T K\, p_l + q_l^T K\, q_l - 2\, p_l^T K\, q_l, \quad (2)$$

where K is a an R x R matrix, with R equal to the number of bins of the histograms. Although the kernel distance from a single link is not always sufficient to detect if a person is obstructing the line-of-sight (LoS) link between two nodes, the kernel distances of several links can be used to localize people. Again, Tikhonov regularization is applied on the reconstructed image.

Our recent results show that, by having the nodes communicating at a very high rate on multiple radio frequencies, the localization accuracy of stationary people can be considerably improved [10]. Thus, both VRTI and KRTI will be modified to consider this feature, and new methods will be applied for correctly merging the data coming from different radio frequencies. The two methods described above are capable of processing the RSS measurements in real-time. Thus, our DFL system is capable of producing position estimates after each TDMA cycle.

3. Conclusion

RF sensor networks have a great potential for improving context-awareness in ambient assisted living applications. In this paper, we describe an RF-based device-free system for localizing and tracking people in domestic environments. The system is minimally invasive, not requiring people to carry any radio device or sensor to participate in the localization task. Moreover, the compact size of the ZigBee transceivers composing the wireless network allows the deployment of several units, even in those locations difficult to reach by wires. To localize people, our system exploits only the variations of the RSS of the wireless links traveling across the monitored area caused by the presence and movements of people. This makes the system robust to changes in the monitored domestic environment, such as opening and closing of windows and doors, or moving of small objects. Two methods, variance-based and kernel-based radio tomographic imaging, process in real-time the RSS data to localize and track people inside the *Living Lab.* For this, the methods use an ellipsoidal model which relates the short-term RSS variance to the distance of the person from the LoS link between two communicating nodes. Also, a TDMA protocol provides high-rate communication over multiple radio frequencies. The RSS data collected on different channels are exploited by both VRTI and KRTI to provide a sub-meter accuracy for the position estimates.

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