Anchor-free Localization in Wireless Lamp Networks using Superimposed RSSI Measurements

A. Caracas, T. Eirich, T. Kramp, M. Oestreicher
IBM Research - Zurich
(xan,eir,thk,oes)@zurich.ibm.com

M. Hoffman, C. Gargiulo, G. Soros
ETH - Zurich
(moritzho,gargiulo,gabor.soros)@ethz.ch

***Abstract*—Localization is a crucial aspect in providing context-aware services and applications. Existing approaches often require a fixed infrastructure or specialized hardware, providing varying degrees of accuracy. For certain application scenarios, high accuracy is not required, if the objects to localize are fixed or slowly moving. For such relatively static scenarios, we propose a novel RSSI-based localization technique using multiple antennas and multiple channels in the 2.4 GHz band. As a concrete application, we present a wireless lighting control system for office lamps in an Internet of Things (IoT) scenario. The lamps participate in a wireless sensor network (WSN) and cooperatively adjust the ambient light based on the self-determined topology correlated with occupancy information. Our experimental results show that we are able to achieve an accuracy of 2 m in 93% of distance estimates with cost-effective IoT technology, improving existing results by 1 m.**

***Keywords*—RSSI-based localization, multi-antenna, multi-channel, wireless lighting**

I. INTRODUCTION

Localization is a crucial aspect for context-aware applications and services. We take for granted and rely on the suggestions given by our navigation systems when driving to a new destination, or, we check the 15-minutes updates of the rain radar before starting the bike journey home. The most prominent outdoor localization system is the satellite-based global positioning system (GPS). However, GPS is not able to provide accurate information or no information at all in certain scenarios. These scenarios occur when the line of sight to GPS satellites is obstructed, in particular, for indoor environments [1] as well as outdoor, in dense forest areas [2], [3] or mountainous regions. In such cases, wireless sensor networks (WSNs) represent a viable, and often the only possible alternative for enabling positioning services [4] in local areas.

In this paper, we focus on improving radio-based localization using the standard received signal strength indicator (RSSI), which is a measurement readily available on off-the-shelf WSNs. One important criterion for our localization system is to operate without any additional infrastructure, e.g. setup and configuration, no fixed beacons, and no extra cabling.

To test the feasibility and accuracy of our proposed localization approach, we concentrate on a concrete application scenario: a wireless lighting control system. We enable lamps, positioned in large, open-office environments, to autonomously determine their location and topology information. Based on this information, and combined with motion detection information, the lamps cooperate in adapting and creating ergonomic ambient lighting conditions.

This paper is structured as follows. In Section II, we discuss related wireless localization systems and how our localization technique advances the state of the art. Following, in Section III, we describe the details of our proposed localization technique. As a concrete application, in Section IV, we focus on an example scenario for a wireless lighting control system. In Section V, we present our experiments and evaluate the results of our localization technique in the context of the lighting control scenario. Finally, in Section VI, we conclude the paper and provide an outlook for future work.

II. RELATED WORK

Localization is an extensively researched topic. Different technologies exist to determine the location of objects in a global or relative frame of reference using various signals (e.g., radio, light, temperature or sound). Due to their extended range, radio-based localization (RBL) systems can be applied to a wide range of environments [4].

In an RBL system, an estimate for the distance between two objects can be obtained based on several techniques such as time-of-flight (ToF), angle of arrival (AoA), or time-difference of arrival (TDoA), e.g. between an acoustic signal and a radio signal. However, such techniques require highly-specialized and time-synchronized hardware [4]. An cost-effective alternative is the received signal strength indicator (RSSI), measured automatically by modern radio chips. This indicator can be related to distance using different path-loss models [5]. However, multipath fading effects significantly affect the accuracy [1] of any RBL system irrespective of the technique for distance estimation.

The best-known RBL example is the global positioning system (GPS). Most RBL approaches, such as GPS, work well for outside environments, far from obstacles or disturbances which may affect the signal propagation. At present, these RBL systems typically utilize a costly infrastructure, based on fixed beacons (in the case of GPS, these beacons are sent by mobile satellites orbiting the Earth) with known positions. For indoor settings, Ubisense [6] provides a commercial RBL solution, based on a fixed beacon infrastructure and highly specialized hardware tags. The tags are able to measure both the AoA and TDoA of beacons signals, which are broadcasted by the fixed infrastructure. Typically such systems operate in the 6-8 GHz (ultra-wide) band as well as the 2.4 GHz band.

In contrast to specialized solutions, the standardized IEEE 802.15.4 radio technology in the 2.4 GHz and 800-900 MHz frequency bands, used by modern WSNs, promises a relatively cheap and off-the-shelf solution for realizing location-based applications and services. This technology is pervasive and applicable to both indoor and outdoor Internet of Things (IoT) scenarios. Because RSSI measurements come at no additional costs, they are performed automatically by the underlying radio hardware of WSNs, we focus on such techniques for eliciting the distance estimates in a cost-effective manner.

Previous work on RSSI-based localization failed to deliver results which were accurate enough for context-aware applications. The best result [7] using RSSI-based localization showed, with off-the-shelf WSN components, an absolute error of less than 3 m (with a probability of 95%). In this case, the application scenario involved a beacon-based infrastructure for improving the tracking of a moving shopping cart in combination with odometric measurements from an inertial measuring unit (IMU). More recent work [8] in this space suggests that using multiple channels can improve the accuracy of RSSI-based localization. However, the authors present no values for the error of the distance estimation.

Most localization approaches focus on tracking moving targets such as controlling cattle in agriculture [9], correlating monitoring information in logistics applications[10], locating shopping carts [7] for marketing purposes, and ensuring rapid response times when elderly persons in assisted living environments [1] are involved. Moreover, available solutions often require a fixed infrastructure, which must be minutely calibrated [6], [1] for best results. However, interesting and business-relevant application scenarios can emerge where relatively static objects (e.g. lamps, computing assets, or shared lab equipment) are able to determine their location without the need of a fixed infrastructure. The self-determined location can be subsequently used as the basis for localizing moving targets.

To summarize, our approach focuses on providing a pervasive, cost-effective, and self-configurable localization solution. Our main contribution addresses the multipath fading by combing RSSI information from multiple frequencies as well as multiple antennas for the same physical location. While we focus on a static scenarios our approach can be extended for tracking moving targets, once the self-configured infrastructure is in place.

III. A NOVEL LOCALIZATION APPROACH

To counteract the detrimental effects of multipath fading, we propose leveraging the different frequencies (also called channels) combined with spacially-separated observations for a given physical position. Such observations are achieved by using multiple antennas, at least half a wavelength apart. For practical purposes, to emulate multiple antennas, we use multiple motes placed next to each other in the same location. To enable a commercial solution, multiple antennas can be controlled by the same radio chip and integrated into a single-mote design.

A. Rationale for Multiple Channels and Multiple Antennas

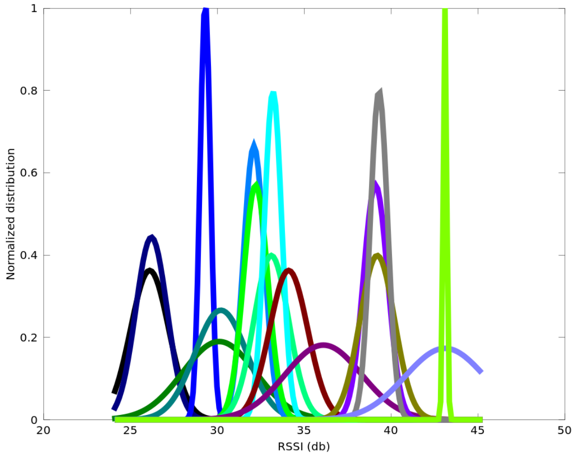

Fig. 1. The distribution of RSSI measurements for individual channels as measured by an observer mote for a given observed mote. When considering the opposite observation direction the RSSI measurements typically follow a similar distribution.

In an ideal case, i.e., without multipath fading, the same RSSI measurements will be reported for all frequencies. (or channels) and for all antennas. By varying the channel, the wave-length is varied, which in turn changes the propagation paths of the indirect signals, because of different reflection patterns. For the direct radio signal, based on Friis's equation [5], the received power is proportional with the square of the wavelength. However, it can be easily shown that for the different wavelengths (of ≈12.5 cm) in the 24 GHz band, the received signal strength would vary by less than 1% at distances of more than 1 m. In other words, some propagation paths will not occur, while others may be induced. The same effect is introduced by placing multiple, spacially-separated antennas in the same location. Intuitively, overlapping RSSI measurements, on different channels, and observed by different antennas, are a very strong indicator for the presence of a component for the correct RSSI value. The RSSI candidate value can then be computed as a linear combination of these strong components.

Using multiple channels and multiple antennas for performing RSSI measurements introduces a new challenge: the different channels report different, albeit relatively stable, RSSI measurements. Fig. 1 shows, for each channel, the distribution of RSSI measurements of the messages sent by the observed mote and received by the observer mote. In our experiments, the difference in the stable RSSI measurements for different channels and different antennas, for the same physical location, were as much as 25 db. The challenge in this case is to select an RSSI value which best represents the distance between the observer and observed mote.

Literature [8] suggest that averaging RSSI measurements across all channels can improve the RSSI-based estimations. However, such a straight-forward approach is biased and extremely sensitive to noise.

B. Selecting the Best RSSI Candidate

Our proposed algorithm for selecting the best RSSI candidate operates in three stages. Because a pair of motes (or

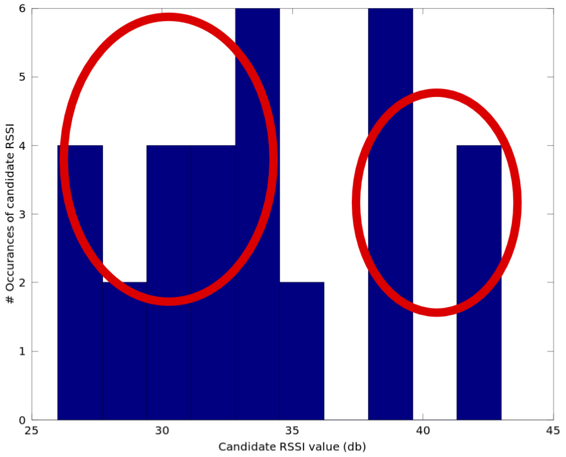

Fig. 2. Distribution of RSSI candidate values for a given pair of motes. The x-axis represents the RSSI candidates, whereas the y-axis shows how many times the RSSI value was selected as a candidate value, for both observation directions and across all channels.

group of motes) corresponds to a single distance, both RSSI observation directions are considered for each distance pair.

In the first stage, the algorithm creates a distribution (histogram) of RSSI candidates. For each channel, and for each observation direction, a candidate is selected based on the most stable RSSI value from the given measurements. Selecting the stable value instead of the mean (which is sensitive to noise) has a significant effect on the final result. Note that in noisy situations, for a given channel and pair combination, it is possible that no selection is made. Effectively, only selections with a minimum confidence (given by the coverage ratio of the stable value) are kept.

Fig. 2 shows such an example distribution of the most stable RSSI candidates for a given pair of motes, where both observation directions are combined. The x-axis shows the candidate RSSI values, whereas, the y-axis shows the number of occurrences (across all channels and both observation directions). For this example, the RSSI candidate value of 39 db was selected 6 times (on 6 channels), based on the measurements performed in both observation directions.

Because we operate on all 16 channels, we obtain a maximum of 32 RSSI selections for each distance pair. In the general case, when grouping motes (treated as multiple antennas) for each distance pair we obtain a maximum of $32 \cdot k^2$ candidate RSSI values, where k is the number of motes (or antennas) in a group.

In the second stage, we filter from the histogram all RSSI values with a low number of occurrences. A low occurrence means there is no correlation with measurements from other channels. The filtering step also separates clusters of RSSI values which are at least 5 db units away from each other. We consider these clusters (shown as ellipses in Fig. 2) to be the strong components for the final RSSI value.

Clusters (marked by ellipses) of most frequent candidates indicate strong components for the actual RSSI value. Note that in comparison to Fig. 1, for a given pair, both observation directions are used. The linear combination of clusters gives an RSSI value which best represents the given pair in terms of the estimated distance. For each cluster c, we then compute the cluster average r_c. Finally, we compute the best RSSI candidate R, which is later used for estimating the distance, as the weighted average of clusters

$$R = \sum_{i=1}^{K} w_c r_c \tag{1}$$

where K is the number of clusters and w_c is the weight for each cluster, obtained as the sum of candidates in each cluster.

In the final stage, we estimate the distance $d(R)$ using the exponential decay path-loss model, which has been widely validated by experimental data [10], [11], [12]. Using this model, the distance estimate can be computed as:

$$d(R) = 10^{\frac{G-R}{10f}} \tag{2}$$

where G is the gain constant, and f is the damping factor.

The damping factor f is specific to a certain environment, whereas, the gain constant G is specific to a certain mote hardware. These parameters can be determined experimentally by applying a least-square means optimization on the measurements with known distances. Alternatively, the parameters can be obtained from previous experimental results [12].

C. A TDMA-based RSSI-collection protocol

To rapidly construct different topologies and for performing RSSI measurements on large areas (requiring multi-hop communication) over extended periods of time, we designed and implemented a custom TDMA-based protocol. We are thus able to gather the individual RSSI observations of each mote in the network. A TDMA-based approach allows the motes in the network to save power because measurements can be performed only when messages are expected. Thus, longer periods of operation are possible with the initial set of batteries. Our protocol implementation uses the IBM Mote Runner platform [13] for WSNs.

Fig. 3 shows an overview of the time slots in the protocol. The protocol uses beacon messages (B) for several purposes: network synchronization, RSSI measurements, and encoding (the computed) topology information. At the beginning of each slot, every mote listens for beacons for a short period of time. This process ensures that the network remains synchronized. Beacons also trigger the initial network formation. Shortly after the beacon, a child mote can request a parent mote for an association (A), which determines the routing tree and occurs in the network formation step.

Once the network is formed (i.e., the routing tree and child parent relations between motes are established), the RSSI values for all received beacon messages are recorded. Beacons are sent by all motes at the beginning of slots of 200 ms. Slots are pre-allocated based on the mote unique identifiers. Based on a round-robin schedule, beacon messages are sent on the full spectrum of available channels (16 channels from 0x0B to 0x21) in the 2.4 GHz ISM band of the IEEE 802.15.4 standard (commonly available for low-power WSN). For each superframe (which acts as a container for all slots), the same

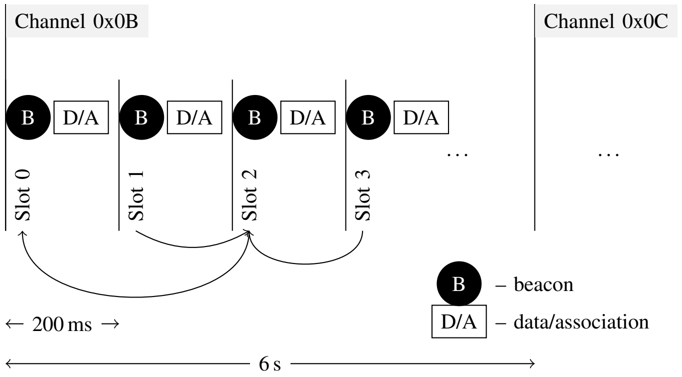

Fig. 3. Overview of slots in the TDMA-based protocol used for collecting RSSI measurements. RSSI values are measured on beacon (B) messages. The measurements are forwarded using data (D) messages, whereas association (A) messages are used to form the routing tree. The arcs show the routing tree between motes to which the slots are assigned to. In this example, the motes in slot 1 and 3 are children of mote 2, which in turn is a child of the edge mote 0. For this example, the slots greater than 4 are yet to be used.

channel is used. In our current implementation a superframe last 6 s, supporting a maximum of 30 slots (or motes). Both the slot duration and number of slots are configurable parameters and can be scaled to accommodate for larger networks.

The remaining time (after the beacon) in a slot is used by child motes to communicate the recorded data (D) to the respective parent. Effectively, motes without children only need to record beacons from other motes and sleep the remaining time. Parents append all the data collected from children to their own data and forward the entire set of measurements towards the edge mote.

Finally, The edge mote is attached to a gateway PC, which saves the measurements locally. The RSSI measurements are then analyzed periodically and transformed into distance estimates.

D. *Topology from Distances*

Computing a physical topology from distance estimates is a well-studied problem and several generic algorithms exists [4], [14] to address this issue. In our experiments, computing the topology using an iterative trilateration [4] approach deemed sufficient for reconstructing a recognizable map for our physical deployments. For larger deployments, which must scale with the number of nodes and limit the cumulative trilateration errors, algorithms derived from the classical multi-dimensional scaling (MDS) method, such as MDS-MAP [15] are better suited [14].

IV. A WIRELESS LIGHTING CONTROL SYSTEM

To demonstrate the feasibility and effectiveness of our localization approach, we are developing a wireless lighting system for open offices. The goal is to construct a system that can autonomously determine the topology of lamps. Based on the self-determined topology combined with motion detector and light sensors, the lamps collaboratively control their outputs in order to create an ergonomic working environment.

The advantages of such an autonomous lighting system is that it requires no time-consuming configuration step compared to existing, wired, central-control systems. Moreover, our system relies on cost-effective technology readily available in modern WSNs and there are no cost associated with cabling. Effectively, such a wireless lighting control system can be installed not only during the construction phase of new buildings but it can also retrofit older (historical) buildings without requiring structural modifications.

Another important requirement for such a wireless system is to allow for convergence times on the order of several hours. Intuitively, best results are achieved outside of normal office hours, i.e., at night time, when (most) humans (and their personal wireless devices) are not present. To a certain extent, the localization algorithm should be robust against moving humans and the noise present during normal office operations. To achieve such robustness, the algorithm requires a longer convergence time, on the order of 4-6 hours. The only assumption is that the objects to be localized, the lamps in our case, are static for the duration of the topology computation.

Effectively, using our system, the lamps only need to be placed at their intended location. Subsequently, they construct a wireless network for bi-directional communication fully autonomously. The wireless network serves as the backbone for measuring the radio signal strength, used to derive the topology of the WSN motes, which are attached to the physical lamps. The topology together with information about motion detection and actual sensed light represent the input which determines the output of the individual lamps. Thus, a finer and context-aware control over ambient lighting can be achieved.

Studies have shown that the lighting conditions and productivity in office environments are correlated [16]. Proper control of lighting and blinds is a crucial factor in reducing the operating costs of buildings [17]. Lighting can also induce psychological effects. For example, anxiety is a natural reaction in a large office space, where the individual working area is lit but the boundaries are entirely dark. In such cases, anxiety can be reduced, and the comfort can be increased, if the perimeter and the walls of the office-space are lit.

A. *System Architecture*

Our wireless lighting solution is structured in three major components as shown in Fig. 4. The office lamps themselves represent the core components. Following the IoT paradigm, each lamp is augmented with an off-the-shelf mote to allow the lamp to participate in a wireless network, which is responsible for running the protocol described in Section III-C for collecting RSSI measurements.

In a commercial setting, the lamp design will be fully integrated with the components of a WSN mote. In other words, the antenna for wireless communication would be indistinguishable from the lamp design, and the MCU and radio chip will be hidden from view. A further design factor may consider using power directly from the lamp supply for powering the WSN mote, instead of batteries currently employed by our development WSN platform.

The second major component of our system is a gateway composed of an embedded PC, with more compute power

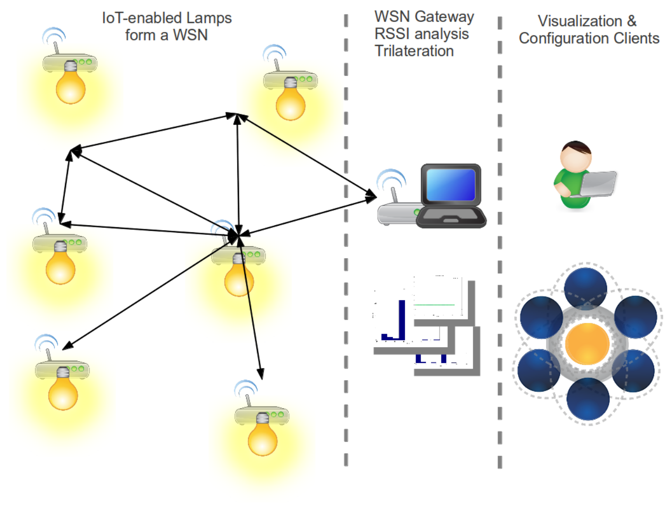

Fig. 4. Architecture overview for the wireless lighting control system. The IoT-augmented lamps form a WSN for collecting RSSI measurements used for automatic localization.

available than the motes attached to each lamp, and an edge mote for connectivity with the WSN. In our current architecture, the gateway is responsible for performing the localization computations and communicating the respective results back into the WSN. In a commercial setting, the localization algorithm can be adapted to run directly on the wireless motes. The gateway runs an embedded Linux distribution and creates a public WiFi (IEEE 802.11) access point to which the visualization client can connect to.

Finally, the visualization component displays the computed topology and the state of the WSN. In addition, the user interface is also intended for setting desired ambient parameters for creating a pleasant and ergonomic working environment. For example, it should be possible to enable a light fading effect towards the perimeter, or setting a brighter lighting in the center of the office space.

V. SYSTEM EXPERIMENTS AND EVALUATION RESULTS

To test the feasibility and accuracy of our localization solution, we conducted several experiments both indoors and outdoors (see Fig. 5). In both cases motes are placed on wooden posts. To emulate multiple antennas multiple motes were placed in groups at the same physical location.

For our experiments, we used standard, off-the-shelf wireless motes, which were deployed in homogeneous networks. To study the effects of different hardware and antennas, we used two platforms: Memsic IRIS motes, with a quarter wavelength dipole antenna, and Atmel AVRRAVEN motes, with a loop printed antenna. Both hardware platforms are based on the same ATMEGA1281 micro-controller operating the same RF230 radio chip, and both run our RSSI-collection protocol on top of the IBM Mote Runner OS [13].

The initial step in our evaluation is determining the parameters for the path-loss model: the damping factor f and the gain constant G. Our measurements confirmed previous experimental results for the damping factor, i.e. $f = 1.8$ for the indoor (corridor) settings and $f = 2.5$ for the outdoor setting. Note that the damping factor applies to both the IRIS and the AVRRAVEN hardware. By contrast, to accommodate for the difference in the antennas, based on the hardware specifications, we used $G = 55$ for the AVRRAVEN motes and $G = 45$ for the IRIS motes respectively.

(a)

(b)

Fig. 5. Indoor (a) deployments using IRIS motes and outdoor (b) deployments using AVRRAVEN motes.

Our deployments used a maximum of 24 motes, which were deployed in different topologies: linear as well as rectangular meshes. To test the effects of spacial separation of antennas we deployed groups of one (1X), two (2X), three, and respectively four motes in the same physical position. The maximum covered area for the outdoors deployments was a field of 200 m^2, with a maximum distance of 20 m between motes. For the indoor deployments, in offices and corridors, we covered a maximum area of 50 m^2, with a maximum distance of 15 m between motes. For both the indoor and outdoor deployments, the motes were placed on wooden (70 cm high) posts to avoid high path fading effects due to proximity to the ground. Measurements were collected over periods of 24 h.

Fig. 6 compares the cumulative relative error for different experimental settings. The y-axis shows the probability that the absolute error of the estimate is below a value of x meters as represented by the x-axis. Our results show that using multiple channels significantly improves the distance estimates when compared to using a single channel only. This result is applicable for both single motes as well as groups of two motes for the same physical location. The results also show that a further improvement of distance estimation is achieved by using two antennas for the same physical location when compared to single antennas. Groups of two antennas (motes) using 16 channels for RSSI measurements achieve a maximum error of 2 m in 93% of distance estimates. Note that simply averaging all RSSI values on all channels increased the error by a few meters. By contrast, single motes using one channel for RSSI measurements, achieve a maximum error of 4.3 m in 90% of the cases.

Our results show that the best estimates are achieved by using multiple channels together with groups of 2 motes placed at the same physical location. In this case, for distances of up to 12 m, we are able to provide distance estimates, which have a maximum error of less than 2 m for 93% of the estimates. The maximum error for all estimates is 2.7 m. Our results reduce the absolute error of distance estimates by more than 1 m compared to previously reported results [7]. For our wireless lighting scenario, where lamps are positioned at least 8 m apart, the absolute errors are well within bounds.

Our experiments also showed that more than two (even

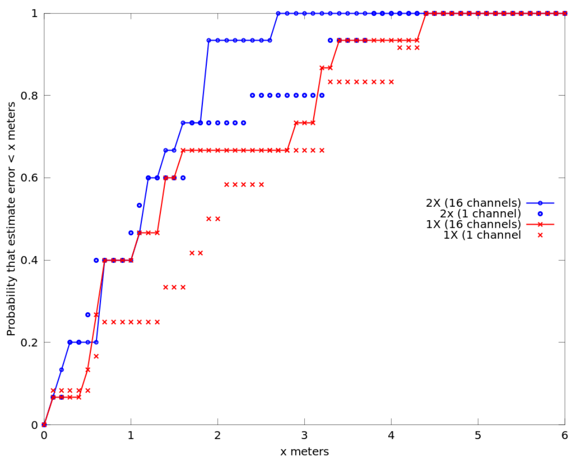

Fig. 6. Comparison between the cumulative relative error for distance estimates for pairwise groups of 1 mote (1X) and 2 motes (2X) using all 16 channels or only a single channel.

though passive) antennas can act detrimentally. In some cases, for three and four antennas, the distance estimates are worse compared to using a single antenna. This represents an interesting aspect for optimizing the antenna design, which is out of the scope of this paper.

VI. CONCLUSION AND FUTURE WORK

In this paper, we presented a novel RSSI-based localization approach, which combines measurements from multiple radio channels and observed by multiple antennas. Our results show that the pervasive, off-the-shelf, and cost-effective WSN technology is able to provide an accuracy of 2m for 93% of estimates for a range of up to 12 m when using two antennas and 16 channels. Such accuracy levels are sufficient for many classes of indoor and outdoor applications.

As a showcase, we presented a wireless lighting control system, currently under development, which allows office lamps to autonomously determine their topology, used to control the lighting. Our localization approach can also be applied to other scenarios, e.g., to eliminate time-consuming, manual inventories for locating computing assets or shared lab equipment. Furthermore, our approach works without the installation and configuration steps required by a fixed beacon infrastructure. Once in place, such a relatively static and self-localized infrastructure can be used to localize mobile objects for both indoor and outdoor scenarios.

For a commercially-viable solution, we envision that the trilateration algorithm will be distributed in the WSN itself, effectively eliminating the need for a gateway. Furthermore, we foresee that the visualization client (e.g., tablet PC or smartphone) can directly connect to any mote in the WSN. This requires either that the smartphones are equipped with radios for the IEEE 802.15.4 standard or that the WSN motes are able to respond using near filed communication (NFC), Bluetooth, or WiFi which represent the norm for wireless communication in the smartphone space.

REFERENCES

[1] M. A. Stelios, A. D. Nick, M. T. Effie, K. M. Dimitris, and S. C. A. Thomopoulos, "An indoor localization platform for ambient assisted living using UWB," in *Proceedings of Advances in Mobile Computing and Multimedia (MoMM)*. ACM, 2008, pp. 178–182.

[2] C. Bo, D. Ren, S. Tang, X.-Y. Li, X. Mao, Q. Huang, L. Mo, Z. Jiang, Y. Sun, and Y. Liu, "Locating sensors in the forest: A case study in GreenOrbs," in *Proceedings of INFOCOM*. IEEE, 2012, pp. 1026 –1034.

[3] W. Xi, Y. He, Y. Liu, J. Zhao, L. Mo, Z. Yang, J. Wang, and X. Li, "Locating sensors in the wild: pursuit of ranging quality," in *Proceedings of Embedded Networked Sensor Systems (SenSys)*. ACM, 2010, pp. 295–308.

[4] Y. Liu and Z. Yang, *Location, Localization, and Localizability*. Springer-Verlag, 2011.

[5] H. Friis, "A note on a simple transmission formula," *Proceedings of the IRE*, vol. 34, no. 5, pp. 254–256, 1946.

[6] Ubisense, http://www.ubisense.net.

[7] P. Coronel, S. Furrer, W. Schott, and B. Weiss, "Indoor location tracking using inertial navigation sensors and radio beacons," in *Proceedings of Internet of Things (IOT)*. Springer-Verlag, 2008, pp. 325–340.

[8] A. Bardella, N. Bui, A. Zanella, and M. Zorzi, "An experimental study on IEEE 802.15.4 multichannel transmission to improve RSSI-based service performance," in *Proceedings of Real-world Wireless Sensor Networks (REALWSN)*. Springer-Verlag, 2010, pp. 154–161.

[9] J. I. Huircán, C. Muñoz, H. Young, L. Von Dossow, J. Bustos, G. Vivallo, and M. Toneatti, "ZigBee-based wireless sensor network localization for cattle monitoring in grazing fields," *Comput. Electron. Agric.*, vol. 74, no. 2, pp. 258–264, 2010.

[10] X. Wang, O. Bischoff, R. Laur, and P. Steffen, "Localization in wireless ad-hoc sensor networks using multilateration with RSSI for logistic applications," *Procedia Chemistry*, vol. 1, no. 1, pp. 461–464, 2009.

[11] D. Puccinelli and M. Haenggi, "Multipath fading in wireless sensor networks: measurements and interpretation," in *Proceedings of Wireless Communications and Mobile Computing (IWCMC)*. ACM, 2006, pp. 1039–1044.

[12] T. Rappaport, *Wireless Communications*. Prentice Hall, 1996.

[13] Mote Runner, http://www.zurich.ibm.com/moterunner.

[14] G. Zanca, F. Zorzi, A. Zanella, and M. Zorzi, "Experimental comparison of RSSI-based localization algorithms for indoor wireless sensor networks," in *Proceedings of Real-world Wireless Sensor Networks (REALWSN)*. ACM, 2008, pp. 1–5.

[15] Y. Shang, W. Ruml, Y. Zhang, and M. Fromherz, "Localization from mere connectivity," in *Proceedings of Mobile ad hoc Networking & Computing (MobiHoc)*. ACM, 2003, pp. 201–212.

[16] S. Begemann, G. van den Beld, and A. Tenner, "Daylight, artificial light and people in an office environment, overview of visual and biological responses," *International Journal of Industrial Ergonomics*, vol. 20, pp. 231–239, 1997.

[17] N. Fergus, M. Wilson, and C. Chiancarella, "Using field measurements of desktop illuminance in European offices to investigate its dependence on outdoor conditions and its effect on occupant satisfaction, and the use of lights and blinds," *Energy and Buildings*, vol. 38, no. 7, pp. 802–813, 2006.