BANDWIDTH EFFICIENT LOCALIZATION FOR SUSTAINABLE AND SAFE BUILDING ENVIRONMENTS

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ABSTRACT

The objective of this work is to propose the use of innovative low-cost wireless sensor network nodes equipped with smart antennas, so as to meet the goal of creating a sustainable and safe building environment. The proposed wireless sensor network system can provide information on people density within building areas, information that can be used in a number of applications such as energy footprint optimization, predictive maintenance and building safe evacuation. The unique design of the proposed sensor nodes can be supportive to the aforementioned applications by providing people location information and building area usage in a bandwidth efficient way, in order to enable such systems to be integrated into existing low-bandwidth in-building communication systems, such as fire alert and automation networks. Node architecture is based on the use of low-cost and low-complexity switched beam antennas and the use of a localization estimation algorithm based on angle of arrival measurements which, as opposed to popular received signal strength based algorithms, are not affected by the severe multipath environment of indoor communications systems.

Index Terms— wireless sensor networks, smart antennas, switched beam antennas, localization, angle of arrival, sustainable environment;

1. INTRODUCTION

One of the most promising technological areas for achieving the goal for a sustainable human environment is the development of smart buildings, capable of reducing their own energy footprint, and of providing information for predictive maintenance actions, without compromising habitants' comfort and safety. The development of smart buildings is based on a number of innovative technologies like wireless sensor networks, sensor and actuator systems, intelligent data processing and fusion techniques, innovative decision support processes, low powered microelectronics and digital signal processing algorithms [1]. Of all the aforementioned systems, the wireless sensor network technologies are there to equip buildings with a digital nervous system capable of providing the necessary information for all other functions [2]. One of the most helpful information that such a network could provide, is localization data. The latter acts as the corner stone for many algorithms that require information on building usage, climate control, air quality control, energy footprint reduction, safety, etc.

Localization algorithms present a significant challenge when applied in WSN that have significant limitations in energy consumption, communication range, bandwidth and cost. These limitations impede the integration of complex digital signal processing algorithms on sensor nodes, and the use of distributed localization algorithms that require the exchange of significant amount of information among nodes. Therefore, current WSN solutions for localization are based on simple received signal strength indicators [3], or on algorithms that do not require range measurements [4]. However, the former has little reliability in severe multipath indoor environments, while the latter suffer from reduced accuracy. In this paper we overcome these problems by introducing a simple distributed localization algorithm, which is less affected from multipath effects, and provides higher accuracy than other non-range-based methods.

The proposed scheme is based on a new generation of miniature low-power wireless sensor nodes which have been recently introduced in [5], and utilize advanced smart antenna technology for continuous monitoring, localization and tracking of events in the network environment. This technology is intended to develop a powerful remote monitoring tool for structural civil engineers that can be used in both new building designs, or be integrated in buildings with an existing low-bandwidth infrastructure for electronic safety and automation systems.

The paper is organized as follows: In Section 2 we present a brief review of the wireless sensor node system which incorporates the use of low-cost smart antenna technology, and of the simple angle-of-arrival estimation scheme which acts as the basic block of the proposed distributed algorithm. In Section 3 we review the problems related to indoor localization, and we present the proposed algorithm as a solution to these problems. Finally, the proposed algorithm is evaluated against a number of parameters in Section 4, and we conclude our work in Section 5.

2. REVIEW OF NODE HARDWARE AND ALGORITHMS

2.1 Brief Review of WiseSPOT nodes

WiseSPOT nodes propose an innovative system architecture, which utilizes directional antennas able to be selected via antenna switching. This system architecture is motivated by the considerable advantages that the use of smart antennas has shown in wireless ad-hoc networks [6], [7]. These advantages, which include range increase, power consumption decrease, and interference cancellation at the network level [8], are quite attractive for WSN applications where range, node power consumption and interference largely dictate the overall lifetime of the network.

WiseSPOT wireless node, illustrated in Figure 1, is based on the M2110 MEMSIC's IRIS OEM Edition module [9], and provides a functional integration of the microprocessor, memory and the wireless transceiver. The latter is compatible to the 2.4GHz Zigbee standard, which is widely used in wireless sensor network applications [10], [11]. The WiseSPOT node utilizes two printed fractal antennas and optionally, two external antennas. In this work we consider the use of the simplest WiseSPOT configuration, without the external antennas. We therefore base our algorithm on the use of nodes that have two back-to-back directional antennas, pointing towards opposite directions.

The node is designed in such a way so that the two radiation patterns are mirror images of each other, and switching between radiation patterns is done through a simple single-pole-double-throw (SPDT) switch, that is controlled by the node's microcontroller. This approach was followed in order to avoid the modification of the physical layer and MAC layer standards, in favor of acquiring higher control of the antenna on the RF front end.

The mirror radiation patterns are produced by high gain and wide bandwidth fractal array antennas. The array antennas cover the whole bandwidth between 2.40 GHz and 2.50 GHz frequencies on which the sensor node transceiver works. The return loss of the antennas is lower than –10dB for the entire bandwidth while the antennas maximum gain reaches 6dBi. This translates to a 3dB azimuth beamwidth of 120^{o} and a Front-to-Back-Ratio of –14dB.

Figure 1: WiseSPOT node with two integrated directional fractal Yagi antennas

The proposed algorithm is based on the use of WiseSPOT nodes, taking advantage of their unique use of switched beam arrays which provide a low-cost solution for determining the angle of arrival of incoming signals, as described in the next paragraph.

2.2 Angle of Arrival Estimation

An Angle of Arrival estimation technique is used based on RSSI measurements utilizing the two directional antennas, placed towards opposite directions, and the ability to switch between each other. More precisely, when data packets start coming from a target node, each WiseSPOT node measures the received signal strength indicator (RSSI) of consecutives packets having only one antenna active at a time. Then, it estimates the AoA of the received signal based on the relation between the two RSSI values. In order to map the ratio of RSSI measurements between the two antennas in relation to the actual angle of arrival of the signal, statistical data analysis has been used based on a series of experiments performed in various building environments. Due to the complexity of such environments in which there are usually many scatterers from metal surfaces, several variations exist in measurements of the ratio of RSSI with respect to the angle of arrival. Two distributions were used to eliminate the scattering effect and ameliorate the accuracy: (1) The polynomial distribution and (2) the Gaussian distribution. The aim of these two distributions is to fit the measured RSSI ratios with the actual angle of incidence of the signal. The average deviation for the polynomial distribution is 20 degrees while for the Gaussian is 19 degrees. Figure 2 shows the maximum and minimum error in each angle. In this figure the mean of the two distributions is used. In most cases, the maximum error is below 15 degrees. Clearly, the ratio of RSSI values for different AoA is largely dominated by the radiation patterns of the two antennas, rather than by the multipath effect of the environment.

Therefore, although the method itself is RSSI based, the actual AoA estimation is less susceptible to multipath fading effects, since the ratio of RSSI measurements rather than the actual RSSI values are considered. The method was first introduced in [12], where multiple beams were used for cellular localization purposes. In our case, although the use of only two antennas produces ambiguities, the proposed algorithm does not need to resolve these, since a general direction of the incoming signals is sufficient, rather than the actual AoA.

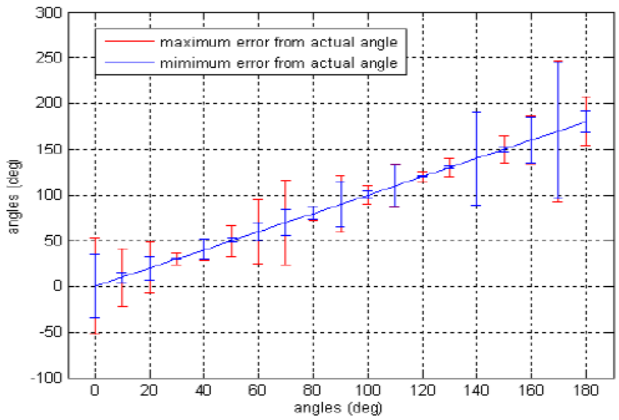

Figure 2: Angle of arrival estimation error using WiseSPOT nodes in indoor environments

3. A SIMPLE DETECTION ALGORITHM

Indoor localization networks designed for building sustainability and safety would have to face a number of challenges. The network of wireless gateways that would enable location estimation would either have to be built upon a new infrastructure with adequate bandwidth for carrying the localization information, it would have to be integrated into an existing infrastructure network, or it would have to rely on wireless multi-hop communication. If we exclude the first solution due to its requirement for increased costs both in new designs and old buildings, the other two solutions provide a backbone network with a considerably low throughput, especially when the number of gateway and mobile nodes is significant. Therefore, the amount of information per user and gateway is critical in such applications. Typically, a localization network should be able to transfer the coordinates of each user, when localization is performed on mobile nodes, or ranging information for each user from each gateway node, when the localization algorithm is performed centrally [13]. Both approaches would therefore require the transmission of a number of bytes over the backbone network for each user and gateway node. Depending on the localization strategy, the gateway nodes that overhear a user would either cooperate locally in order to reduce communication overhead, would send all information centrally, or would suppress information from most of the overhearing nodes according to an RSSI threshold [4]. The first approach increases the complexity of the wireless network multiple access scheme, and also increases the demand for computational capacity of wireless gateways. The second approach increases the traffic load of the backbone network, and the last approach may have severe consequences to the accuracy of localization.

Based on the analysis above, we conclude that if the localization system could provide the required accuracy

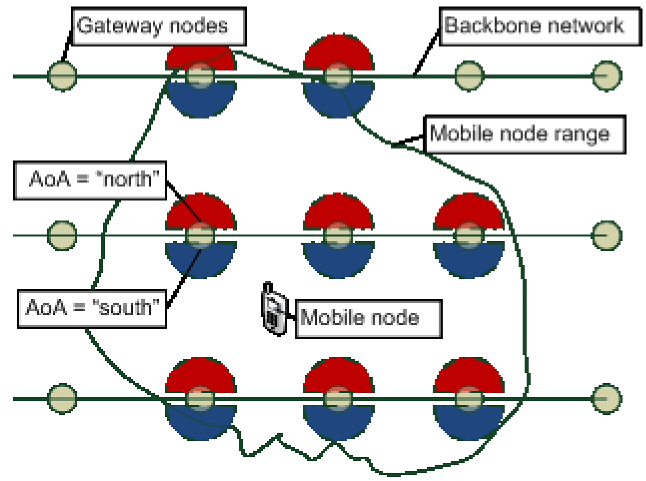

Figure 3: The proposed localization network

with minimal amount of information per node, we would be able to use a localization algorithm run centrally, while meeting the low bandwidth limitations of the backbone network. For this purpose, we propose the use of nodes equipped with switched beam antennas in order to provide a solution to the aforementioned problems, by implementing the following simple localization algorithm which is based on the angle of arrival estimation method described in the previous Section.

We assume that the gateways of the network are placed in known locations, and that the orientation of their antennas is known. Consider for example the network described in figure 3, where the antenna beams are aligned on the north-south axis. Gateway nodes are presented to be placed on a rectangular grid, which would be a typical case if for example such nodes are integrated in the building's smoke detector system. Using this configuration, each gateway node may locally compute the AoA of the signals received from mobile nodes in range, as described in the previous Section. Instead of transmitting full AoA information, gateways just need to send a single bit per user, depending on whether the mobile node is detected towards their "north" beam, or their "south" beam. For example, if the AoA estimation algorithm outputs a value less than 90 degrees, this is translated as "south". If it outputs a value of more than 90 degrees, this is translated as "north". This information is collected in a central station, which knows the gateway coordinates and their antenna orientation. From this information, the central station will be able to derive estimations on each user's location in the following way: by detecting the grid row where the AoA changes from "north" to "south", it may find the exact row that the user lies in. Moreover, by calculating the center of gravity of the overlapping area of the active gateways' beams within this row, the central station can provide an estimation of the exact location of the mobile node.

The proposed algorithm resembles a "presence detection" algorithm, which is well known in wireless sensor networks for its low complexity and low communication overhead. However, by using the advantages provided by the use of smart antennas, the accuracy of the proposed scheme is much higher, as demonstrated in the next Section.

4. PERFORMANCE EVALUATION

The proposed algorithm was simulated in a typical building floor configuration, where gateway nodes are considered to be placed inside smoke detectors, on the ceiling. We consider a 10 by 10 rectangular grid of such gateway nodes, forming a network of 100 active nodes with known locations and antenna orientation. Mobile nodes using omnidirectional antennas are placed randomly within the grid and are localized using the algorithm described in the previous section. We only consider the use of directional antennas on gateway nodes, and not on mobiles, since the stricter dimension limitations of the latter would not allow for antenna structures larger than those of a single omni-directional element.

The performance of the proposed scheme is compared against other low-bandwidth localization schemes that do not make use of the angular information that sensor nodes equipped with smart antennas can provide. We therefore consider as a benchmark an equivalent setup that would use RSSI measurements to determine whether the mobile node is within each gateway's range. This information, which can also be coded into a single bit, is transmitted and processed centrally, in order to produce location estimations.

We evaluate the performance of the proposed scheme taking into consideration two key parameters: detection beamwidth, and mobile node range. Detection beamwidth stands for the angle range within which a gateway node will activate a transmission of a detection bit towards the central station. For example, if the detection beamwidth is 100 degrees, then a gateway node will send information to the central station only when the AoA of the incoming signal is within 40 to 140 degrees (sending "north") or -40 to -140 degrees (sending "south"). If the AoA is detected to be within -40 to 40 degrees or 140 to -140 degrees, no information will be sent towards the central station. It is noted here that the detection beamwidth is not the antenna beamwidth. It is a parameter of the algorithm, which is utilized after the AoA detection process described in Section 2.2.

All errors and ranges are expressed as a fraction of the distance d between two consecutive gateways on the grid, which is a defining parameter of the system performance. In figure 4, the error of the proposed scheme is computed with respect to the detection beamwidth, and compared against the omnidirectional case. It is evident that the larger the detection angle, the larger the error, since more distant gateways are involved in the computation of the location within the same row. Moreover, large localization errors are produced for small detection angles. This quite interesting result has the following explanation. When the detection angle is small, then the gateways that have the smaller distance to the mobile node, will not activate detection messages towards the central station. Only distant gateways will generate such messages, resulting in large estimation errors. The smallest error is evidently produced for detection beamwidths equal to 90 degrees, and these are significantly smaller than the errors produced by the benchmark method. Although this result was produced for a mobile node range of 3d, it is shown in figure 5 that this small error remains unaffected by the node range, as opposed to the omni-directional detection method.

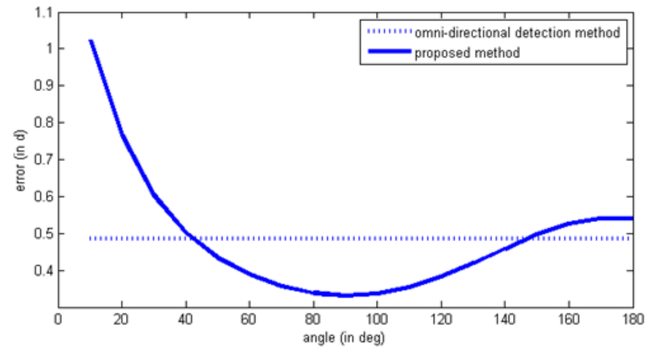

Figure 4: Estimation error in respect to detection beamwidth (where d is the grid size)

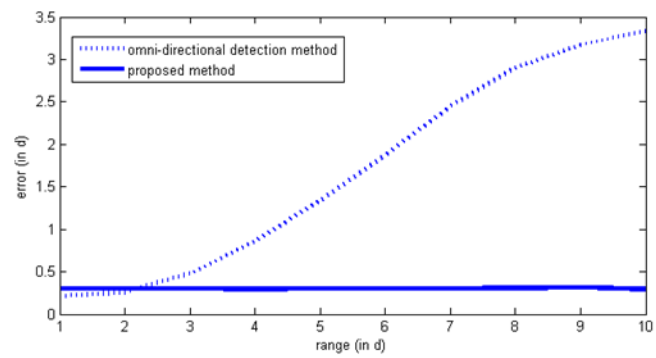

Figure 5: Estimation Error in respect to mobile node range (where d is the grid size)

5. CONCLUSION

In this work we presented a simple, bandwidth efficient distributed localization algorithm, which provides significant accuracy for applications where building usage and occupant presence is required. Such applications could include energy consumption optimization, predictive maintenance, or even safe building evacuation. The proposed scheme is based on the use of wireless sensor nodes equipped with switched beam antennas, and takes advantage of the nodes' robust angle of arrival estimation capabilities, to overcome typical indoor propagation problems, and to provide accurate localization information over a low capacity backbone network. The proposed algorithm is run centrally, requiring only a single bit per user and gateway node. Simulated results have shown that even under severe multipath conditions, the proposed scheme convincingly outperforms other low-bandwidth schemes that use omni-directional antennas and make no use of angular information.

6. REFERENCES

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