

A WIRELESS SENSOR NETWORK FOR CLEANROOM MONITORING

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Abstract: A Wireless Sensor Network (WSN) is under development for deployment into a cleanroom environment, in order to obtain information on personnel location, machine usage, and environmental parameter distribution. This paper presents the system concept and architecture, reports on the accuracy of Received Signal Strength Indication (RSSI) locationing in an indoor environment and provides details of the developed WSN to Ethernet bridge.

Keywords: wireless sensor networks, location sensing, received signal strength indication

INTRODUCTION

A key architectural design aim of the new cleanroom at the University of Southampton (replacing the previous one that was destroyed by fire in 2005) is to increase the visibility of the activities and work being undertaken inside. This project is developing a Wireless Sensor Network (WSN) for implementation in such an industrial environment, to obtain information including personnel location (who is working where, and what they are working on), machine usage (which machines are in use), and 2-d environmental parameter distribution (such as ambient noise, light or temperature). Data obtained from the WSN are reported to a remote computer which presents the information via local display screens (shown in Fig. 1) and the intranet/internet.

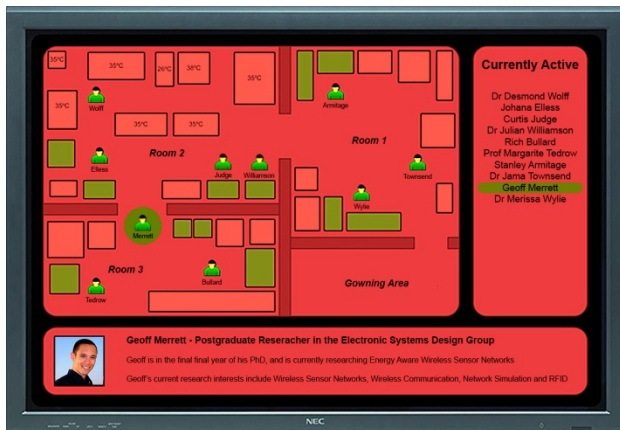


Figure 1. Prototype public display screen for the cleanroom WSN, displaying personnel locations and activities, machine usage, and temperature distribution.

This project aims to provide the following functionality:

- **Publicity and Awareness.** The WSN 'opens up' the cleanroom for visitors, students and staff, making a level of information that cannot be obtained by simply looking through windows readily available.
- **Administration.** Productivity of cleanroom users can be improved by allowing them to see which machinery and areas are in use via an intranet interface, reducing wasted visits. Additionally, simple paging functionality can allow researchers

elsewhere on campus to communicate with cleanroom users. Furthermore, through the monitoring of machine use, the system can collate statistics on how often machines are used, helping technical staff identify rarely-used equipment which can be turned off or removed.

- **Research Platform.** The system provides an interesting and evolvable platform for research into all aspects of WSNs.

The system architecture (a simplified version of which is shown in Fig. 2) consists of a number of heterogeneous nodes with differing capabilities, functionality, and design.

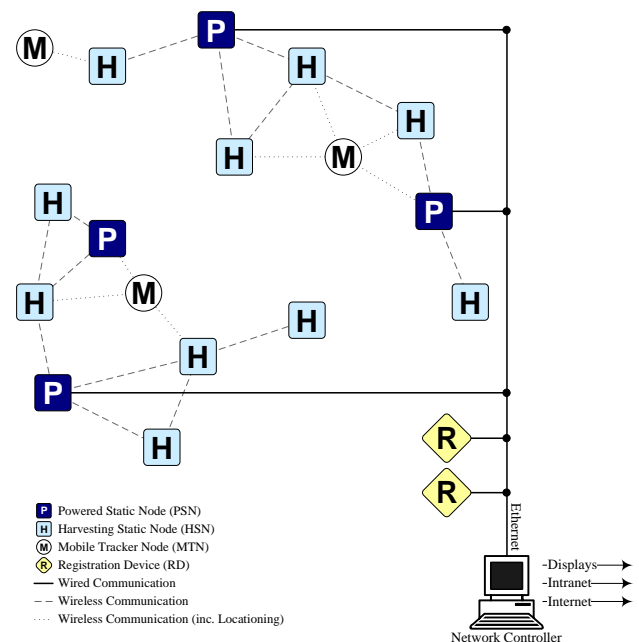


Figure 2. The system architecture of the cleanroom WSN.

Mobile tracking nodes (labelled 'M' in Fig. 2) are small, locally-powered, wearable nodes worn by users of the cleanroom in order to identify and locate them, and permit simple paging functionality. Mobile tracking nodes calculate their location through communication with a number of harvesting or powered static nodes located on benches or machinery (labelled 'H' and 'P' respectively in Fig. 2), which also obtain information concerning bench and machine usage, and provide the network's communication backbone. Static nodes report

packets using multi-hop routing to in-network sink nodes that are connected to the intranet/internet via Ethernet. The network controller (a remote computer) is also connected to the intranet/internet, and outputs received data to display screens and the intranet/internet. Additionally, one or more registration devices (labelled 'R' in Fig. 2) allocate and associate nodes to users.

This project encompasses a wide range of different areas of research and disciplines, including low power design, energy management, networking, communications, and locating/target tracking. This paper investigates the suitability of using Received Signal Strength Indication (RSSI) to locate personnel within an indoor environment, and presents a developed interface between the wireless (WSN) and wired (Ethernet) networks.

RSSI LOCATING

Clearly, a fundamental requirement of this WSN is the ability to locate the mobile tracking nodes (and hence the users) in the network. A range of techniques exist for locating nodes [1, 2], including the trilateration of separation distances calculated using Time of Arrival (ToA) or Received Signal Strength Indication (RSSI), multilateration using Time Difference of Arrival (TDoA), or triangulation using the Angle of Arrival (AoA).

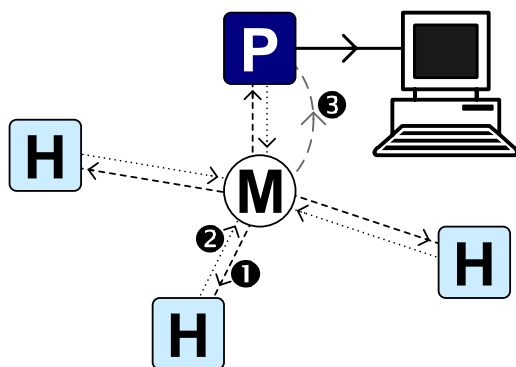


Figure 3. A simplified representation of RSSI locating. 1) The mobile tracking node broadcasts a sequence of packets, and the static nodes take average RSSI measurements (this is only labelled at one node, but occurs at all). 2) The mobile tracking node receives a packet from each static node (containing the RSSI value calculated in step 1) which it fuses to calculate its estimated location. 3) The mobile tracking node reports its estimated location to a sink node (over one or more hops), which forwards this data to the network controller over a wired medium.

This paper considers RSSI trilateration using the hardware location engine integrated in the Texas Instruments CC2431 [3]; a System-on-Chip (SoC) integrating an eight bit 8051 microcontroller and IEEE 802.15.4 [4] compliant radio transceiver. As the locating requirement of this application is to obtain only a 'reasonable' estimation of the user's location (to infer the area in which they are working), an accuracy of a few metres is acceptable; the

CC2431's location engine claims an accuracy of better than three metres, with a resolution of 0.25m.

RSSI uses the received signal strength from multiple nodes at known locations to infer the distances from these nodes, and hence trilaterate the node's own location (as shown graphically in Fig. 3). This process obviously relies upon a relationship (which is known or approximated) between the received signal strength and the separation distance; a commonly used empirical model is the log-distance path loss model (1), where $P_R(d)$ is the received signal power [dBm] at a distance d [m], d_0 is the far-field reference distance [m], and η is the path loss exponent [5].

$$P_R(d) = P_R(d_0) - 10\eta \log_{10} \left(\frac{d}{d_0} \right) \quad (1)$$

It can be seen through inspection that the algorithm used in the CC2431's hardware location engine (2) is derived from the log-distance model, where $d_0 = 1\text{m}$, and A is equal to $P_R(1\text{m}) * -1$ [6].

$$RSSI(d) = -A - 10\eta \log_{10}(d) \quad (2)$$

To 'tune' the operation of the algorithm to the target environment, best-case values for A and η in (2) were obtained through empirical measurements. Through 80 measurements of the received signal strength at a separation distance of one metre, the mean path loss was found to be -41dBm (with a standard deviation of 0.48dBm); therefore A was chosen to equal 41. Through performing similar tests at various locations in the environment, a value of $\eta = 3.375$ was found to provide the most accurate results (this level of precision is enforced by the CC2431's hardware engine, which requires the designer to use path loss exponents from a discrete set with separation of 0.125).

To provide a form of energy-aware location reporting (of importance to this application), the mobile tracking nodes only report their location when their estimated position has deviated by more than a particular distance threshold (where the node reports its location when $\Delta x^2 + \Delta y^2 \geq \delta^2$, where Δx and Δy are the change in x and y coordinates respectively since the location was last reported, and δ is the distance threshold). This management of the node's location reporting stops the node wasting energy through the sending of redundant location packets. Furthermore, the value of the distance threshold can be controlled by the energy state of the node, using the IDEALS/RMR system [7]; as the energy in the node's energy store depletes, the tolerance on the known location of the user increases.

In order to evaluate the CC2431's locating ability, a network of six static nodes and one mobile node was deployed in an indoor office environment (shown in Fig. 4). As seen in this photograph, the environment contains a large number of obstacles, interfering devices, and sources of reflection; we believe that this provides a rough approximation to many of the conditions witnessed in a cleanroom.

The six static nodes were situated on top of the dividing screens to ensure that line of sight (LOS) was usually possible between static nodes.



Figure 4. The indoor environment into which the WSN was implemented and evaluated.

The six static nodes were located as shown in Fig. 5 (labelled 'SN'). This plan view maps to the photo in Fig. 4 where the camera is at a coordinate (20,2) and looking in the direction of (0,10). The estimated location of the mobile tracking node was recorded at five different locations in the room (labelled by the black shapes in Fig. 5), and this was repeated 20 times at each location. Fig. 5 also shows the mean estimated location following these measurements (labelled by grey shapes), showing limited location accuracy in a room of this size, especially in the y-axis, where all estimations are within two metres of each other. While for many applications this level of location inaccuracy could be considered unacceptable, it is sufficient here (where only a rough approximation of user location is required). However, this research is being continued with the aim of improving these results to ~1m accuracy.

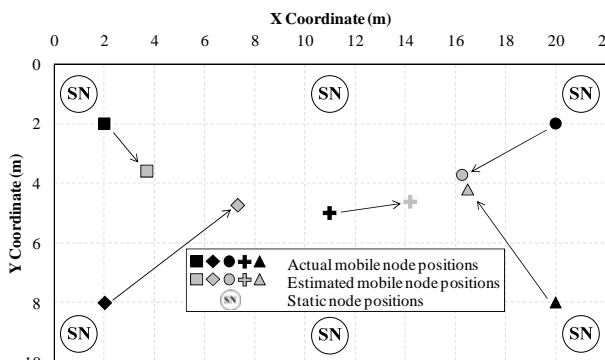


Figure 5. The accuracy of the RSSI locationing using the CC2431 in an indoor environment (where the arrows point from the actual node location to the 'estimated' location).

These results are also given numerically in Table 1, which can be compared with Fig. 5 using the various shapes representing the node test positions. These results show that the average error in the mean estimated location is over four metres. However, the location error standard deviation is reasonably small, confirming that this error remains consistent between subsequent measurements of the same location.

Table 1. Location Accuracy Measurements

Identifier in Fig. 5	+	■	●	▲	◆
Real Location	X:11.0 m Y:5.0m	X: 2.0m Y: 2.0m	X:20.0 m Y:2.0m	X:20.0 m Y:8.0m	X:2.0m Y:8.0m
Mean Estimated Location	X:14.2 Y:4.6	X:3.7 Y:3.6	X:16.3 m Y:3.7m	X:16.5 m Y:4.2m	X:7.3m Y:4.8m
Mean Estimated Error	3.3m	2.5m	4.2m	5.3m	6.3m
Error Standard Deviation	0.63m	1.24m	1.32m	2.19m	0.2m

The causes for the limited location accuracy observed are many. Firstly, as can be observed in Fig. 4, the deployment environment contains a very large number of obstacles causing signal attenuation, including dividers, pillars, lights and desks, in addition to reflections caused by these obstacles and the floor, walls, windows and ceilings. This results in the received signal strength varying considerably from the path loss model shown in (2) however well the parameters are tuned. This is confirmed by the consistent nature of the error in accuracy (highlighted by the standard deviation in Table 1), which would be expected in complex environments such as this. Secondly, the half-wave antennas used do not provide a uniform radiation pattern meaning that, even in free space, the signal strength will vary at different points that are a distance d from the transmitter. As trilateration is having to make a best guess based upon a number of distance estimates (unlike traditional geometric problems where 'known' distances are accurately determined, the 'known' distances in this situation are only estimated and contain error), a single node providing an inaccurate distance estimate may considerably offset the calculated location.

These results suggest that the CC2431's RSSI location engine may not be suitable for precise locationing in cluttered indoor environments, given the limited accuracy found in this study (where all estimations are tending towards the centre of the network). The limited accuracy is particularly interesting considering that LOS was usually present. It is the belief of the authors that RSSI, as a technology, should be able to perform better in this environment and, hence, current research is considering alternative RSSI algorithms on other hardware platforms. Furthermore, other techniques such as ToA may enable further improvements, and are the subject of continued research.

It is important to note that, as previously specified, the application requirement is not to locate users accurately at a fine resolution, but instead to achieve an indication of which area they are working in, and at which workstation they are located. To this end, RSSI using the CC2431 hardware engine with only minor improvements may be sufficient, especially if coupled and fused with information from additional

intelligent sensing. Examples of this fusion could include using machine usage data (if a machine is currently in use, it is likely that the user located closest to it is using it), the user's history and research profile (to identify which machines they are likely to be using), or computer vision techniques (using the WSN to ascertain the identities of the users working in an area, but using computer vision or passive infrared [PIR] sensors to locate them).

WSN/ETHERNET INTERFACE

As previously discussed and shown in Fig. 2, the sink node(s) and registration device(s) communicate with the remote network controller via Ethernet, to enable the off-site processing and control of the network. To realise this, the sink node (a standard static node) passes packets containing location estimates to a PIC microcontroller via SPI. The PIC formats this data, and manages the transmission of a User Datagram Packet (UDP) over Ethernet using a SitePlayer module [8]. The developed system is shown in Fig. 6, though it should be noted that its size can be considerably reduced (in Fig. 6, the CC2431 node, PIC microcontroller, and SitePlayer module are all situated on development boards).

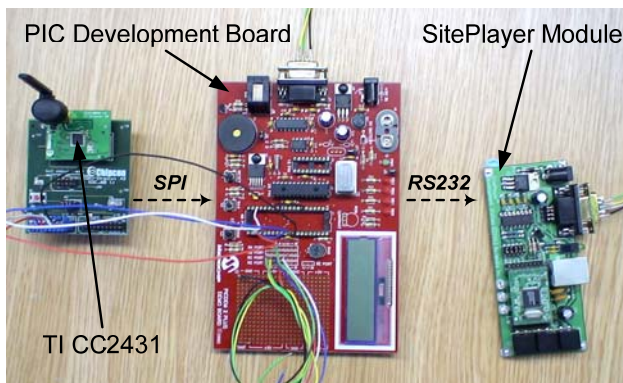


Figure 6. The developed bridge receives IEEE 802.15.4 wireless packets via SPI, and uses a PIC to format data packets and 'push' them over the internet using UDP.

The transmitted UDP packets are received by the network controller, using software that receives the packet, and presents the data containing the location estimates on a graphical display screen similar to that shown in Fig 1. Because UDP is designed for applications that do not require guaranteed delivery, a complete communication protocol was implemented to sit above UDP in order to provide flow control and acknowledged data transfer (based upon Stop and Wait ARQ [2]). The protocol was designed to allow the simultaneous acknowledged communication between the network controller and multiple sink nodes. To implement this protocol, the sink node's PIC is required to manage retransmissions, packet queues, and sequencing.

This sink node interface was used for obtaining the location estimate results presented in the previous section. Further information on the implementation of the sink node interface, the network controller, and the communication protocol is available on request.

CONCLUSIONS

This paper has outlined the concepts and architecture of the cleanroom WSN at the University of Southampton. This application demands a WSN, as obtaining reasonably unobtrusive personnel location, machine usage and environmental parameters through a retrofitted system could not be effectively achieved using conventional techniques.

This paper has presented an evaluation of the CC2431 hardware RSSI locationing engine in indoor environments. It has been found that the location estimates exhibit limited location accuracy (an average of over four metres in a deployment area of 10m x 22m). However, this level of accuracy is acceptable in this application due to the requirement for 'approximately' locating users. It is the authors' belief that the error is caused by a combination of limitations in the CC2431 hardware location engine and in the cluttered nature of the indoor deployment environment (a fundamental limitation of RSSI locationing). To reduce the error, the investigation of RSSI using other hardware or alternative techniques (such as ToA) are areas of ongoing investigation.

This paper has also described the developed WSN to Ethernet bridge, enabling the network controller conceived in this application.

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