SensorTune: a Mobile Auditory Interface for DIY Wireless Sensor Networks

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ABSTRACT
Wireless Sensor Networks (WSNs) allow the monitoring of activity or environmental conditions over a large area, from homes to industrial plants, from agriculture fields to forests and glaciers. They can support a variety of applications, from assisted living to natural disaster prevention. WSNs can, however, be challenging to setup and maintain, reducing the potential for real-world adoption. To address this limitation, this paper introduces SensorTune, a novel mobile interface to support non-expert users in iteratively setting up a WSN. SensorTune uses non-speech audio to present to its users information regarding the connectivity of the network they are setting up, allowing them to decide how to extend it. To simplify the interpretation of the data presented, the system adopts the metaphor of tuning a consumer analog radio, a very common and well known operation. SensorTune represents the first attempt to apply mobile sonification to the domain of WSNs. A user study was conducted in which 20 subjects setup real multi-hop networks inside a large building using a limited number of wireless nodes. Subjects repeated the task with SensorTune and with a comparable mobile GUI interface. Experimental results show a statistically significant difference in the task completion time and a clear preference of users for the auditory interface.

Author Keywords
Mobile HCI, Mobile Computing, Sonification, User Study, Wireless Sensor Network, Network Deployment

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces

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INTRODUCTION
The increasing availability and miniaturization of sensing and computational devices, together with their decreasing cost promotes a wide adoption of sensor-based applications. The resources to store and process the data they gather are similarly more available and cheaper. Complex sensor-based applications used to be only affordable in military or industrial environments. The range of possibilities now expands to office and home contexts as well as urban and agriculture environments. Example applications of sensing technologies include enhanced environmental monitoring conditions to prevent natural disasters [9, 14, 25] and to support agriculture, especially in disadvantaged areas [17, 21]. In the domestic context, one of the most compelling applications is probably assistive technology and tele-care/home-care (systems that allow patients in their homes to be remotely monitored by healthcare specialists), which becomes more and more important in the context of an aging population [1].

One proposed architecture to practically enable large scale sensing applications, from buildings to city-scale to entire natural resources on the dimension of glaciers, is a *Wireless Sensor Network* (WSN). WSNs consist of multiple autonomous electronic devices, named *nodes*, distributed over the area to be monitored. Each node has the ability to sense data, process it, and transmit the information to other nodes. Normally one node acts as a collection point where the data is aggregated and consumed (displayed, further processed, or transmitted to a remote location). WSNs are widely regarded as an enabling technology for ubiquitous computing and the precise monitoring of human, urban and natural environments alike. However, this promise will be hard to fulfill as long as WSNs remain as difficult to install and maintain as they are today. Even afer scientific questions (choice of sensor and sampling strategies) and technological issues (hardware, software, packaging) have been addressed, it is commonly reported in the WSN scientific literature that deploying a wireless sensor network can be a cumbersome and labor-intensive task [22, 23, 21]. Achieving a successful WSN deployment is essentially a matter of optimizing the placement of sensor nodes, given possibly antagonistic constraints, such as *connectivity* (ensure that all sensing nodes can communicate their data to the appropriate destination), *network life-time* (maximize the average battery-life, i.e. minimize power consumption), and *deployment and maintenance costs* (minimize total number of nodes). In particular the influence of the environment on network connectivity is often difficult to diagnose due in part to the limited display capabilities of wireless sensor nodes. These difficulties are exacerbated when the network topology is sparse (for instance WSNs for agriculture), or when the environment is particularly challenging for the radio channel (an indoor environment with metallic walls or pipes, etc.) In contrast, because of the wide range of applications they support, WSNs should be made accessible to users who are not experts on wireless communication and computer networks.

In this paper we introduce *SensorTune*, a novel mobile interface to support non-expert users in iteratively setting up WSNs, and especially the node placement with respect to the connectivity constraint. SensorTune uses non-speech audio to present the user information regarding the connectivity of the network they are setting up, allowing them to decide where to position new nodes to extend the network. To simplify the interpretation of the data presented the system adopts the audio metaphor of searching for a station through the AM or FM radio band – a very common and well known operation – by conveying information about connection quality through the amount of noise degradation. The deployment and monitoring of WSNs normally requires users to physically navigate in the environment, which is a fundamentally visual task. The use of auditory displays can be highly advantageous in these situations in eliminating the need to switch visual attention between a display and the environment (Figure 1). No prior work was found to address the support of non-expert users setting up a WSN, or to investigate the application of sonification to wireless networks.

From a strictly technological point of view, SensorTune is a tool to support the setup of *ad-hoc multi-hop wireless networks*; *ad-hoc* meaning that they do not rely on a fixed infrastructure and *multi-hop* in the sense that individual nodes are not only sources and destinations of information but they also forward information generated and addressed to other nodes, so that the geographical extension of the network can be larger than the range of an individual radio transmitter.

Figure 1. SensorTune in use. The shoulder bag carried by the user contains the monitoring device (Figure 2) and the nodes to deploy. Information is presented through the headphones, so users' hands are free. The user holds the node he is currently deploying, notice on the back of the box magnets used to attach it to metallic surfaces. On the left of the photo, a node that was deployed earlier.

Even though the two are not exactly equivalent, we use the term *Wireless Sensor Network* rather than *ad-hoc multi-hop wireless network*, because in fact most WSNs use an ad-hoc multi-hop configuration and we want to place emphasis on this type of application.

The next section provides an overview of related work, followed by the description of SensorTune, covering the motivation behind the system, its design and the implementation of a prototype. We then report and discuss a user study to compare SensorTune with a similar mobile GUI interface – in the study 20 subjects setup real multi-hop networks inside a large building using a limited number of wireless nodes.

RELATED WORK

The idea of using a PDA for field-inspections has been discussed by Buonadonna et al. [5] in relation to the TASK project. The TASK field tool provides the ability to ping a single node, issue a command to turn on an LED or a buzzer, or to reset the node. Similarly, Ringwald et al. [22] propose an in-field inspection tool on a compact device for collecting information about the node states. It also enables the actual users of the WSN to perform routine checks such as displaying the network topology, or uploading new firmware versions. Lifton et al. [11] developed the Ubicorder, a mobile device used to browse and interact with already deployed WSNs. Sensors are displayed as animated dots on a map of the environment centered around the position of the user. It is also possible to control how information is presented, combining for example data from several nodes using an adjustable set of parameters and rules. In each of these cases, the feedback given to the user is visual, not sound-based. We believe sound to be better adapted to deployment tasks, the real challenge being to provide intuitive feedback in that form.

In the area of deployment-support tools, Ringwald et al. [22] emphasize the necessity of passively inspecting the network in order not to disturb it and modify its state. Consequently, they designed a deployment-support network (DSN) overlaid on the network to be monitored, communicating with it on a back-channel. This approach supposes a heavy infrastructure to be deployed in parallel with the monitored network, and requires the nodes themselves to have dual radios. In contrast, our approach is more light-weight: SensorTune only needs a limited snapshot of the node's state and its connectivity with the rest of the network, thus limiting the interference caused by the application to the WSN.

Selavo et al. [23] recognize what they call the deployment time validation (DTV) as an "indispensable" part of fielding a real system. They developed a deployment time validation approach, named SeeDTV, based on a simple communication protocol between a master node and a deployed network, and an in-situ user interface device, called SeeMote. The feedback is given to the user through a small screen adaptable to a node. Our approach is similarly lightweight, but we explore the use of a different interface paradigm, based on auditory feedback, emphasize its originality and analyze its specific advantages in our context.

Sonification refers to the use of audio signals (mostly non-speech) to convey information. The use of sound to display information is not new: early examples include alarms, the telephone bell, the Geiger counter and medical instrumentation [10]. However, over the last decade this field has drawn increasing attention, mainly due to the growing amount of scientific data to display and the improving technology for processing audio. Barrass and Kramer provide a presentation of sonification, its usefulness, approaches and issues, as well as a list of resources [2].

Sonification research has often investigated applications targeted at expert users: either users expert in the acoustic domain (e.g. people with a music background) [19] or experts in the application domain, such as computer network experts [8, 13, 20]. Therefore mapping strategies generally leverage users' advanced knowledge or ability to detect sound qualities to provide a rich output that displays multiple data dimensions at the same time, associating each of them to different audio synthesis parameters such as pitch, loudness, duration and timbre. As discussed below, our approach is targeted at non-expert users, so it favors simplicity at the expense of multidimensional output.

Different projects investigate the application of sonification to monitor computer networks. The Peep [8] and NeMoS [13] systems provide a framework for associating different network traffic conditions and events to the generation of sound, while Qi and others [20] focus on intrusion detection and denial-of-service attacks. All of them differ from what we propose in the present paper in that they are targeted at advanced users –network administrators– rather than non-experts. Moreover, their purpose is to monitor existing fixed networks, rather than to set up a wireless one, and usability experiments have not been reported for any of these systems. A number of media art and popular science projects explored the sonification (and visualization) of radio signals; examples include the work reviewed in the "Hertzian Tales" book [6] and S. Kato's "2.4GHz Scape"[1]. Generally these projects are purely driven by aesthetics or have a *critical design* nature, intending to raise public awareness of radio transmission. While they are powerful sources of inspiration, they generally do not attempt to support users in specific tasks.

Several studies have compared the use of auditory and visual displays in a variety of tasks and application domains. Most of them found that, in the specific domains studied, the performance of subjects using an auditory modality is as good or even better as with a graphical interface. In a visual search task, Brown et al. [4] gave a cue about the position of the target using either an auditory or a visual modality. No difference in terms of performance was found between the two groups of subjects. Pauletto and Hunt [18] conducted an experiment comparing the ability of visual and auditory interfaces to represent basic information about complex time-series data sets. The subjects were asked to rank five attributes of data (e.g. noise, repetitions, etc.) on a series of data sets presented in a visual or auditory way. A high correlation of rankings between both modalities was found, showing that the auditory modality is a valid alternative to visual displays to represent this kind of information. Valenzuela et al. [24] applied sonification to support the interpretation of signals obtained from the nondestructive testing of concrete. The auditory interface allowed subjects to learn how to interpret signals significantly faster than using a visual display. Moreover, subjects were successful in transferring the auditory learning to a real-life situation. In an experiment comparing the ability of non-experts subjects to predict the future direction of stock prices using either an auditory, a visual or a mix of both modalities, Nesbitt and Barrass [15] found no difference on the subjects' overall performance.

We could find only one study showing a negative effect of an auditory interface. Loeb and Fitch [12] compared the accuracy and the speed of detection and identification of critical events in physiological data. Results showed that subjects were less accurate using the auditory interface, but it was attributed to a too short training time and some design issues.

In the context of mobile applications, Brewster and Murray [3] used *Earcons* –short sounds associated to UI elements: ear icons– to improve the presentation of dynamic information on mobile devices. A comparison with the traditional visual-only modality in a stock price's monitoring task showed that the use of sonification reduced subjects' workload and their need to switch between several displays.

The study presented in this paper contributes to these results by addressing the use of sonification in the field of WSNs and, more importantly, compare its effectiveness with a GUI in a real mobile application.

SENSOR TUNE

Motivation

Wireless Sensor Networks (WSNs) are designed to monitor various forms of activity over a large physical area. Given the wide range of applications they support, WSNs should be made accessible to users who are not wireless communication or computer network experts. For normal functioning of the system, all nodes in the WSN need to have a direct or multi-hop[2] connection to a specific node, referred to as the *base-station* or *gateway* node. This node is connected to an external unit or to a long range connection transferring data in a remote location, which uses the information to display or analyze the sensor data collected by the entire network. Nodes are generally designed to be as inexpensive as possible and to require very little power, making battery replacement as infrequent as possible. Consequently, nodes lack any display units, except perhaps a few LEDs.

To consider a more practical example, in a rural agriculture context the base station may be physically hosted in a house, where equipment for data display, analysis or long range transmission is more safe and easily accessible. In the same context, because of limited resources, it may often be desirable to use the minimum number of nodes to cover the largest possible area, leading to a sparse configuration.

[1] http://homepage.mac.com/oto_s/ITP/EBYM.htm

[2] connection as a route going through several nodes forwarding data toward destination

Setting up a WSN is challenging because choosing where to install a new node requires an understanding of radio signal propagation and knowledge of how well other nodes, already part of the network, are connected to each other and to the base station. Moreover, additional constraints for the node positions may be present. For example if the node has to measure soil moisture, it may need to be close to the ground. A typical approach to set up a WSN would traditionally require users to rely on status LEDs available on the nodes, and to use 2 extra nodes, running a ping-pong application, as probes. This kind of approach requires some understanding of low-level concepts of networking (e.g. ping) and the use of a difficult-to-interpret display. The design of SensorTune was driven by a wish to make this process easier and more accessible to users who are not experts in networking.

Design

SensorTune enables users to monitor in real-time the connectivity of a node that they want to add to a WSN[3]. A pleasant continuous sound, e.g. a piece of classical music, indicates that the node has a connection (direct or indirect) with the network base station. When the connection is good, only the pleasant sound is audible. When the connection quality degrades, noise is added to the pleasant sound. When the connection is lost, users hear only noise, without the pleasant sound. In the case of a connection with a node which is disconnected from the rest of the network, a so-called *orphan* node, SensorTune plays a repeated bell in place of the pleasant sound. Two types of noise are used to indicate loss in connection quality: higher frequency noise indicates a degradation of the connection with the closest node, while lower frequency noise indicates a degradation of the connection between the closest neighbor and the base station. The intensity of the two types of noise is weighted to give more importance to the local connection.

SensorTune allows the iterative setup of a WSN according to the following steps, repeated as many times as the nodes to be placed, starting from the base station:
1. a new node is turned on in physical proximity to an already active node, so that the new node can establish a radio link with the old one and therefore with the rest of the network. SensorTune plays a pleasant sound reflecting the good connection.
2. Users start to walk away from the old node, looking for an appropriate position for the new node. SensorTune lets them understand when they are too far from other nodes in the network because the pleasant sound gets increasingly corrupted by noise until it is not audible anymore.

SensorTune uses only audio to convey information to its users. While a visual interface can be very powerful for network monitoring as it can present complex network information both synoptically and analytically, our design aimed at creating a representation that could be minimal and easy to understand for non-specialist users. The deployment and monitoring of WSNs normally requires users to physically navigate in the environment. Navigation is primarily a visual task, which may be particularly demanding in areas that are not easily accessible. The use of auditory displays eliminates the need to switch visual attention between a display and the environment which can be highly advantageous in such situations. Moreover, considering that the most common portable graphic displays are hand-held, the use of audio outputs also frees the users' hands, which can be used to support or balance the body in difficult situations.

From the hardware and physical construction standpoint, audio displays, such as loudspeakers or headphones, present considerable advantages compared to graphical displays: they are less expensive, require less processing power and consume less energy. From the ergonomics point of view, visual displays are often problematic for outdoor usage, where the contrast provided by LCD screens is often insufficient.

Interface metaphor

The mapping strategy used in SensorTune can be interpreted as a metaphor for the tuning of a consumer analog radio, an action that is familiar to most people around the world: when a radio station is perfectly tuned, the audio is clear, when the tuning is not centered, or the radio signal is weak, the audio is corrupted by noise. The emphasis is not on realistically mimicking the analog radio tuning effect, but on providing users with a model that is easy to interpret. The proposed strategy leverages the assumption that even non-expert users of WSNs will have some understanding of a system relying on radio transmission. The use of noise or distortion is not common in the auditory display literature, despite its strong metaphorical valence. This is perhaps due to the concern of confusing degradation generated by the interface with real degradation affecting the system. The advent of digital technology, however, allows for an easier control of the presence of noise or distortion, to the extent of completely eliminating analog noise, as demonstrated by the use of comfort noise in digital communication systems [16].

The sound indicating good connectivity can be chosen according to the taste of the end-user, so that different cultural backgrounds can be accommodated. However, it is important that the sound chosen is easily distinguished from noise. For minimizing memory consumption, a loop is used for the pleasant sound, selected to be long enough not to be annoying and to loop in a seamless way (discontinuities could be perceived as signal degradations). In the prototype evaluation described below we used a 16-second clip of classical piano music.

Implementation

From the technical point of view, SensorTune aimes at minimizing the disruption of nodes that are already deployed in the network and to limit communication overhead and its consequences on power consumption. For this reasons, only the node newly introduced in the network and its immediate neighbors are affected by SensorTune. Relevant information about the status of the rest of the network is derived from the routing tables which are calculated and stored in all nodes independently of our system. The cost of such lightweight approach is that SensorTune cannot provide users with infor-

[3] an audio demonstration of the system is available on http://web.media.mit.edu/ enrico/SensorTune

mation about the status of the entire network, but only about the local nodes and their connectivity to the base station. As a consequence, SensorTune aims at helping users to create a *robust* network configuration, even though this will likely not be truly *optimal*.

SensorTune includes a portable monitoring device equipped with headphones and with a radio transceiver capable of communicating with the WSN nodes. When a node is turned on within the radio range of the monitoring device, it is set in *scanning mode*: the node periodically queries all neighboring nodes and calculates the best link to the base station. This calculation of the link quality is based on 2 factors: the quality of the single-hop link between the scanning node and its neighbors (which is estimated in real time) and the quality of the link between each neighbor node and the base station (which is periodically calculated by the network routing algorithm and stored locally on each node). The quality of the best link is communicated from the scanning node to the monitoring devices which renders it as audio, according to the mapping described above. The scanning node is switched to standard operation as soon as a new node is turned on, or when the monitoring device is deactivated.

A prototype was implemented using wireless nodes running TinyOS [4], an open-source operating system for WSNs. The SensorTune monitoring device was implemented on a Nokia N800 PDA, equipped with headphones and connected via serial port to a modified TinyOS node, as shown in Figure 2. The implementation involved the development of an application running on the WSN nodes, and one running on the monitoring device (distributed between the N800 and the node physically connected to it). On the nodes, the application reused much of the networking code included in TinyOS, including the link quality estimation. The N800 was chosen for prototyping because of the availability of the PureData audio software for this device [7], which made it possible and easy to explore different sonification strategies before adopting the current one. The implementation was in nesC (an extension of C for TinyOS) for the software components running on the nodes and in a mix of Java, Python and PureData for those running on the PDA.

TinyOS allows the system to run on a number of different hardware platforms. We tested it on TinyNode584[5] and micaZ[6] devices, which are application-generic WSN nodes commercially available. The user study reported in the following section was run using TinyNode devices because of their longer radio range.

EVALUATION

Design and Methods

A user study was designed and conducted to validate the design and implementation of SensorTune, with two objectives. First, at a general level, the study aimed at assessing whether the system enables non-specialists to deploy a

Figure 2. The components used for the SensorTune prototype: N800 PDA, TinyNode and headphones.

wireless sensor network in a challenging setting with minimal training. Second, more specifically, we wanted to evaluate the presentation of network-related information through sonification, compared to the presentation of *the same information* in a different format: visually.

Design

The study was centred around a network setup task, carried out with the support of SensorTune. To evaluate distinctively the effects of the network information provided by SensorTune and the presentation format through the audio metaphor, the sonification interface was compared to a simple graphical user interface (GUI) presenting the same information. It should be noted that while a more advanced GUI could easily be designed to display additional information, our emphasis was on displaying the very same information as in the audio interface. This information is minimal because of the lightweight monitoring approach described in the previous section. Our hypothesis was that the performance of the participants using the two user interfaces would be comparable.

Subjects were asked to create an ad-hoc multi-hop network connecting one starting point to two destination points, in a 'Y' configuration within the building of our department, using at most 8 TinyNode devices, as illustrated in Figure 3. The nodes were housed in plastic boxes equipped with magnets, so they could be attached to metallic surfaces present in our setting (such as furniture and pillars). In pilot studies it was observed that participants may take different paths between the start and destination point, effectively finding shortcuts which may make the task easier. Finding shortcuts appeared to be a random event, not related to the type of interface being used, acting as a disturbing factor for the comparison of the two conditions. For this reason in the current study subjects were asked to follow a specific physical path between start and destinations; they could place the nodes anywhere in the rooms crossed by the path (some are quite large), but not outside them. Because of the nature of the task, it was not possible to ask subjects to repeat the experiment with a different interface over the same path, as they could simply position the nodes in the very same locations

[4]http://www.tinyos.net
[5]http://www.tinynode.com/
[6]http://www.xbow.com/Products/productdetails.aspx?sid=164

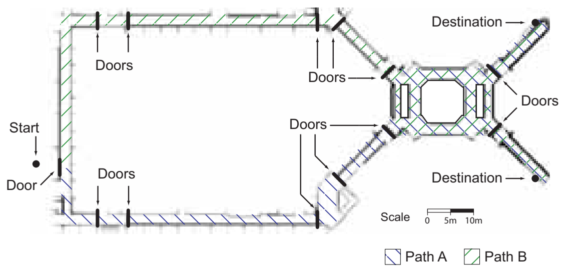


Figure 3. The two paths used for the experiment.

as in the previous trial. Therefore, two paths, "A" and "B", of comparable length (approx. 150m) and difficulty connecting the start point and the two destinations were defined, as illustrated in Figure 3. The paths are not completely symmetric – otherwise subjects could simply mirror the nodes configuration used earlier.

Both paths presented a number of challenges. They do not have a line-of-sight and they include doors and other physical obstacles, mimicking the challenges of a real place where a WSN may be used. Because of the physical obstacles, nodes cannot be simply placed equidistantly from each other. Attempting to solve the task with this strategy would result in failure, because the 8 available nodes would not be enough to create a connection. The two paths were challenging enough to provide a sufficient ground for the study, and offered considerable freedom in the node placement, while still allowing relatively controlled experimental conditions. Over each path, the task could be completed within 20 minutes with the available number of nodes. Expert users (outside the group of subjects in the study) showed that through path A it is possible to create a connection with a minimum of 6 nodes, while path B required a minimum of 7 nodes. Working indoors was necessary to avoid variability in brightness levels due to time of the day or meteorological conditions, a concern because glare may cause difficulties in reading the screen when using the GUI interface.

Apparatus

For the SensorTune condition, participants used the prototype described in the previous section. For the GUI conditions, we developed a user interface with two horizontal bars, illustrated in Figure 4, each displaying the quality of the connection to the nearest node, and the connection of this one to the rest of the network. This type of visualization resembles what is common in mobile phones: a bar visualization of the connection quality. It was thus considered to be an obvious alternative to the sonification interface. In addition to mobile phones, this type of display can also be found in personal computers (for example to display the connection quality of wifi networks) and in home audio systems (to visualize the volume level). The GUI was displayed on the screen of a Nokia N800 PDA, the same device used for the audio interface, which was carried by the participants during the experiment. The 3 GUI buttons visible in Figure 4 were only used by the experimenter and participants were instructed not to press them.

Participants

Subjects were recruited from the university through mailing lists. The advert stated clearly that no previous experience or knowledge about WSNs networks was required, no inclusion or exclusion criteria were defined and anyone who expressed interest was allowed to take part in the study, as long as they were able to walk for the duration of the experiment (2 sessions of about 20 minutes each). 20 subjects aged 18 to 34 (M=23, STD=4) took part in the study. All of them were students at the bachelor, master or doctoral level with an engineering background except for one of them who was studying business. Even though some of them may have had specialist and advanced knowledge in other domains of technology, the vast majority (see below) reported to have little or no prior experience with WSNs. This condition may represent early adopters of WSNs, who may have interest in sensing driven by expertise in other domains, but who are not wireless and multi-hop radio experts.

Procedure

The study design was repeated measure, where every subject tried both interfaces, each on a different path. The order of the experiment was fully counterbalanced: half of the subjects started with the Audio interface and half started with the GUI, in each of these conditions half of the subjects started on path A and half on path B, for a total of four combinations. Participants received written instructions, presented through a web page on a standard personal computer. The instructions introduced the system and the tasks to be completed. Some background information related to WSNs was also given in the instructions. For example, it was suggested not to leave nodes on the floor if possible, as that is known to attenuate the radio signal. Subjects were instructed to complete the task within 20 minutes using the minimum number of nodes and achieving the best connection quality they could. They were informed that these requirements were in conflict and required a trade-off. Task completion time was not mentioned explicitly in the instructions besides the 20 minutes limit per task; in pilot studies it was observed

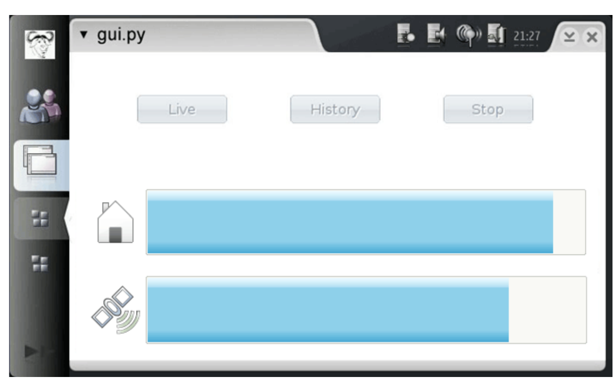
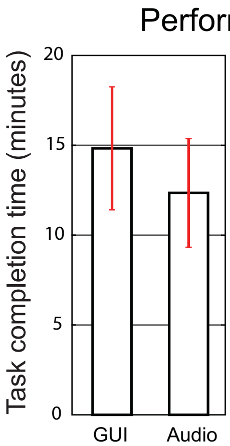


Figure 4. A GUI presenting the same information provided via audio. The top bar represents how well the neighbor is connected to the base-station, while the bottom bar represents the quality of the connection with the closest node.



Category	T. C. T. (minutes)	Nodes
GUI	14.83 (3.42)	7.45 (0.51)
Audio	12.35 (3.02)	7.2 (0.77)
Path A	13.39 (3.50)	7.1 (0.72)
Path B	13.79 (3.43)	7.55 (0.51)
1st trial	13.64 (3.39)	7.35 (0.67)
2nd trial	13.54 (3.55)	7.3 (0.66)

Figure 5. Left: average task completion time using the two different interfaces, with standard deviation error bars. The difference is statistically significant according to ANOVA analysis ($p < .05, F = 5.29$). Right: average performance measures for different conditions, standard deviation in parentheses.

that asking the subjects to complete the task as quickly as possible induced them to go too fast and fail the experiment, as they would not wait long enough to check that the connections between the nodes was stable. In this way we expected subjects to work at reasonable pace but still not need longer than necessary to complete the task, as they knew they were being observed. After reading the instructions participants were walked through the path joining the starting point and the destinations, and then they were shown SensorTune in action. They were given a shoulder bag containing the 8 nodes to be used for the experiment. In the audio UI condition participants wore headphones and the PDA was also placed in the bag, for a true hands-free setup. In the GUI condition the PDA was held by participants with one hand.

Measures

Performance was measured in terms of task completion time and number of nodes used. An experimenter shadowed the participants, taking note of where they placed nodes, of their general behavior and making sure that the technical aspects of the systems were working correctly. The minimization of task completion time may in itself not be a primary goal for the design of tools supporting the deployment of WSNs. In the experiment this measure was used as an intermediate metric to compare the performance of different interfaces. This choice was based on the assumption that a more comfortable and effective interface, everything else being the same, would lead to a faster task completion.

After subjects completed both tasks they were asked to fill out a questionnaire, presented as a web form, on the same computer used for reading the instructions. The questionnaire included questions about the subjects personal data and general background, as well as subjective evaluation of the interfaces used and prior knowledge and experience with WSNs and radio propagation. In particular subjects were asked which interface they found easier to use and why and which interface they found more efficient to use, as the one which let them perform better and why. Note that this is based on subjective perception of one's own performance, which may or may not correspond to factual performance. Both questions allowed "Audio", "GUI" or "Same" as answers. The specific background questions asked whether users were familiar with ad-hoc networks before the experiment, if they had experience with setting up such a network before the experiment and whether they were familiar with radio propagation. In all 3 questions subjects were asked to provide more details in case of positive answer.

The entire experiment took about 1 hour, including the 2 20-minutes tasks plus the time to read the instructions and fill out the questionnaire.

Results

Performance Measures

All subjects were able to complete both tasks within 20 minutes. The general average task completion time was 13.43 minutes (STD=3.44) and the number of nodes used 7.33 (STD=0.66). A 3-way 2nd order ANOVA analysis of the task completion time using the interface (GUI or Audio), the path (left or right) and the repetition (1st or 2nd time) showed that the different interfaces have a statistically significant effect ($p < .05, F = 5.29$), while there is no effect from the other factors, nor any interaction. The same ANOVA analysis was performed on the number of nodes used to complete the task. In this case the different path have a statistically significant effect ($p < .05, F = 4.83$), while there is no effect from the other factors, nor any interaction. The results are displayed in Figure 5. No correlation was found between the two performance measures.

Node Positions

It was observed that in some parts of the paths, especially towards the beginning, subjects had a tendency to be more consistent with each other regarding the nodes position. However, in other parts more variability was observed. This confirms that the task was not trivial, could be solved in different ways with varying degrees of effectiveness and thus reflected a real-world situation. As an example, node locations chosen by two users during the study are reported in Figure 6.

Interface Preferences

In the subjective ratings, 15 out of 20 subjects found the audio interface easier, 2 found the GUI easier while 3 rated them as the same. In terms of efficiency, 13 subjects preferred the audio interface, 5 the GUI and 2 found the 2 interfaces as efficient as each other. Histogram plots of this data are shown in Figure 7.

The reasons expressed by participants who preferred the Audio UI over the GUI were grouped into 5 broad categories: *hands-free / eyes-free*, *easy to interpret*, *emotional factors*, *smooth variations* and *other*. Examples in the *hands-free / eyes-free* category included: "[...] you don't need to focus on the screen. You can walk listening to the audio system, but with the GUI it is not so easy to walk while looking at it." Comments categorized as *easy to interpret* included: "more intuitive. You can worry about finding a place for the nodes

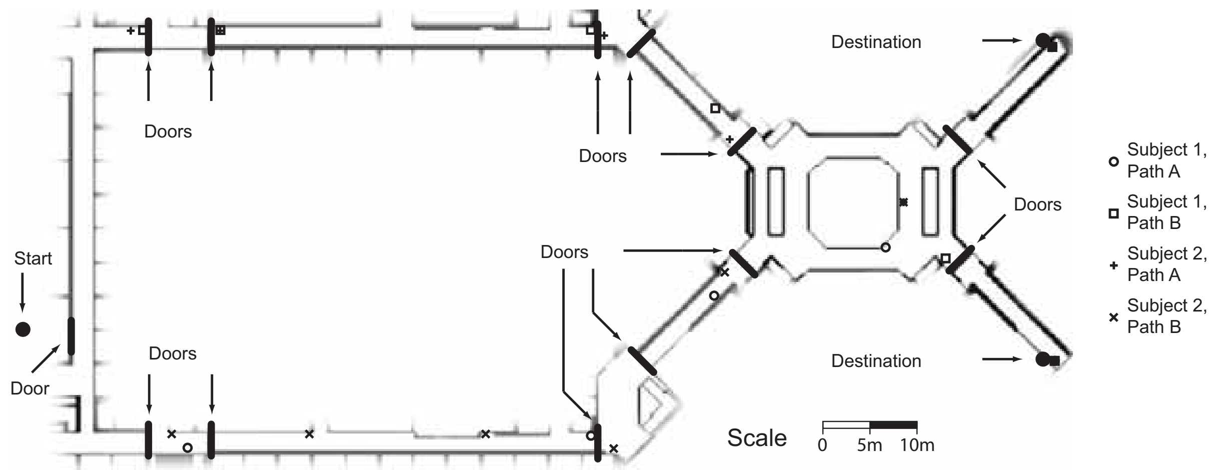


Figure 6. Example node locations from 2 subjects who took part in the user study.

with your eyes while your ears inform you about the signal quality"; "It is clear what the information you're given means."; "the quality of the sound is easier to judge than the graphic bar". Example comments classified as *emotional factors* included: "I find more relaxed setting up multi-hop wireless networks listening Bach" or "because I trust my hear [sic] more than [the] computer indicator". Example comments classified as *smooth variations* included: "GUI was annoying, the signal was changing all the time". The summary of the classification is shown in Figure 8. Some subjects made comments which fell across different categories, in this case they were counted in all of them.

Conversely, the reason for preferring the GUI included: "the visual feedback was easier to interpret" and "I think the GUI method is more efficient because you have more accuracy with signal level".

Participants Background and Expertise

The questions relative to the subjects prior knowledge and experience with WSNs and radio propagation were in open form. To facilitate the analysis, two coders collaboratively converted the answers to a 5 point scale, ranging from "1 - no prior knowledge" to "5 - expert". The results are reported in Figure 9.

A correlation test was run between the values obtained for the subjects prior knowledge and the performance measures and with the preferences about the interfaces. Statistically significant positive correlation ($r = 0.3, p < .05$) was found only between task completion time and prior experience with WSNs. No significant correlation was found between any other pairs of measurements.

Qualitative Observations & Other Comments

Different behaviors were observed during the experiment. Sometimes subjects showed a more *aggressive* strategy, trying to stretch the connection distance as long as possible: they would try to walk as far as possible from previous nodes and then walk back after losing connection. In other cases a more *protective* behavior was observed: subjects would stop as soon as noticing a small degradation in the connection quality. During an individual trial subjects could show a tendency for a specific behavior, or switch between the two.

Doors had a considerable effect on the propagation of the radio signal connecting the nodes, even though they did not all appear to attenuate the signal in the same measure. Some subjects were quick in picking up the effect of doors, and started using this knowledge in the task, others appeared always surprised of a loss of connection through a door.

Discussion

The results confirm that SensorTune helps users to create a WSN, because all subjects completed the task within the al-

Figure 7. Participants' preferences after trying both interfaces.

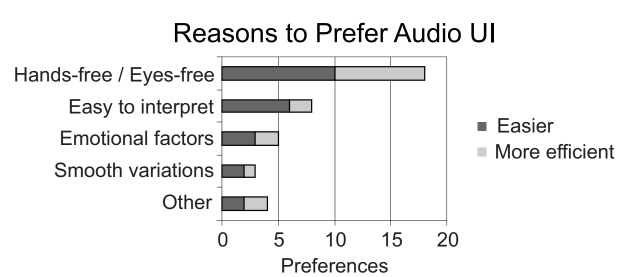


Figure 8. Reasons to prefer the Audio interface over the GUI.

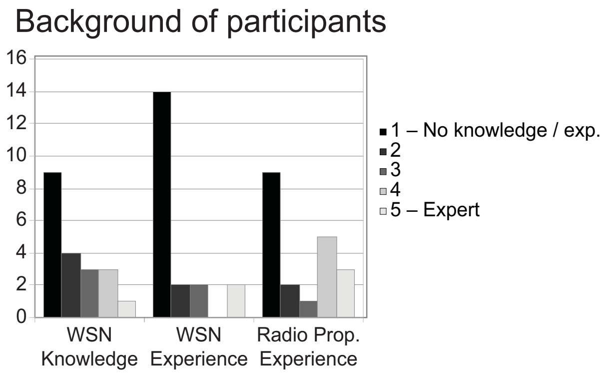


Figure 9. Background knowledge and experience participants had before the experiment.

lowed 20 minutes, regardless the specific conditions. The majority of participants (14) had no prior experience in setting up multi-hop wireless networks: they were novices to the experimental task. This is reinforced also by the correlation between task completion time and prior experience with WSNs. It was, at first, surprising that the Audio interface outperformed the GUI in terms of task completion time. The comparison was originally planned to check whether the performance of the two UIs would be comparable, because even with comparable performance an auditory interface provides comfort and safety advantages for being hands-free and eyes-free that would make it preferable over a GUI. The faster performance with the audio interface can partially be explained by the fact that participants could move and open doors faster when using the GUI; each path included 7 doors, and these were often used more than once as subjects tended to go back and forth through them. The significant difference in the average number of nodes between the two paths confirms the difference found by our expert users, as discussed in the experimental design.

The strong preference expressed by users for the audio interface validates our design choices, especially if we consider the motivation for their preference. The most popular reason to prefer the audio interface, either in terms of ease of use or perceived efficiency was its being hands-free and eyes-free. The second reason for preferring the sonification, the ease of interpretation of the information provided, can be tracked back to the interface metaphor, confirming the appropriateness of our choice.

The results of our experiment suggest that audio can be used to effectively deliver information in an interface for WSNs. Beyond the advantages outlined in Section 3, in a mobile context it can be useful to use both modality of output, offloading some of the information from the screen (often of reduced size on mobile devices) to the auditory channel. Future work should address the integration of audio and visual output, to obtain a richer interface. The two modalities could be integrated in a redundant or complementary fashion, either presenting the same information across the two modalities to allow users to choose the one they prefer, or showing some information through sound and other through a GUI.

The quantitative results confirm that the two paths used in the experiment are roughly equivalent. Despite the fact that expert users were able to complete Path A with one fewer node than Path B, no statistically significant differences were found either for the number of nodes users used in the two paths or for the task completion time.

It was interesting to notice the different aggressive or protective behaviors users took. Unfortunately we lacked a protocol to more precisely observe whether the different user interfaces had influences on this aspect. Similarly, it was not possible to understand whether the interfaces had an effect on the mental model developed by the participants. It may be interesting to try and develop an experimental protocol for future studies to further analyze these aspects. In particular, it may be possible to use the application logs to detect such behaviors.

FUTURE WORK

The SensorTune interface can be extended to address different phases of a WSN life-cycle – not only the setup phase, but also the maintenance. In particular we are interested in extending the system to be able to interactively query the status of the connection at a given node over a specified period of time. A new *mode* can be added to the interface to allow users to browse the past history of signal strength at different time scales. From the sonification point of view, further work should investigate the use of different audio mapping strategies, as alternatives to the one presented in this paper. Future studies should investigate the applicability of SensorTune to more complex network topologies, for example node placement leading to tree topologies in the routes to the base station. Field studies should be organized in locations where sensor networks are deployed, and with subjects extracted from the real user population.

CONCLUSION

This paper introduced the design and user evaluation of SensorTune, a novel mobile interface to support non-expert users in setting up WSNs. SensorTune leverages the metaphor of tuning a consumer analog radio, an operation which is very common, to provide users with information about the quality of connectivity of the network they are building, allowing them to decide where to position new nodes introduced in the network. Results from a user study where 20 non-expert users had to setup a WSN show that when using SensorTune participants completed the task faster than with a comparable GUI, with statistical significance.

No prior work was found to address the support of non-expert users in setting up a WSN, or to investigate the application of sonification to wireless networks. Therefore, we hope that the results presented in this paper, as well as the reported experimental methodology, will stimulate discussion and further work related to human-computer interaction and WSNs. HCI research opportunities are present not only in the deployment phase, but also in relation to monitoring, analysis and visualization of the data gathered.

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