MULTITONE ACOUSTIC SENSOR NETWORK WITH MOBILE ACCESS: AN EXPERIMENTAL TESTBED

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ABSTRACT

Sensor network with mobile access (SENMA) was proposed as an architecture for large scale sensor networks. With promising results in analysis and simulation, we have developed an experimental testbed for SENMA using indoor acoustic transmission. Indoor acoustic signal shows a similar propagation characteristic to radio frequency (RF) transmission in a manageable physical dimension. It shows the average attenuation with distance and fading due to multiple reflections from walls. In this paper, we describe the system design of acoustic SENMA testbed and its application. The developed system includes the basic features of SENMA such as the mobile access point(s), transmission of beacon signal, probabilistic transmission depending on channel state, and multiple access from the sensors. We use the frequency division multiple access (FDMA) in the uplink where sensors transmit acoustic tones in different frequencies. The reception models such as collision channel and signal to interference and noise ratio (SINR) model can be applied and the network performance like throughput is calculated based on the processing of the recorded sound from the sensors.

Index Terms - Sensor Network with Mobile Access (SENMA), Acoustic Channel, Frequency Division Multiple Access (FDMA), Beacon Signal, Channel State Information, Opportunistic ALOHA.

1. INTRODUCTION

Recently sensor networks have drawn much attention for many applications such as environmental monitoring, scientific research, and surveillance. A large number of sensors are expected to be distributed across a geographical area to gather and process information from the sensor field. For large scale sensor networks, the design of system architecture and protocol to form a network and retrieve the sensor data is a challenging task [1]. Many authors have proposed various architectures including flat *ad hoc* networks or hierarchical *ad hoc* networks, for example, [2].

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Sensor network with mobile access point (SENMA) was proposed to reduce the protocol overhead of multi-hop *ad hoc* networks and increase the energy efficiency of sensor operation by eliminating the necessity of routing and relaying information from sensors[3]. In SENMA, there are two types of nodes: sensors and mobile access points. Sensor nodes have sensing and basic communication capability. Complicated functions like forming a network is done by powerful mobile access points or interrogators (e.g., unmanned aerial vehicles) which move around the sensor field and gather data from sensors via multiple access control such as the opportunistic ALOHA. (See Fig. 1).

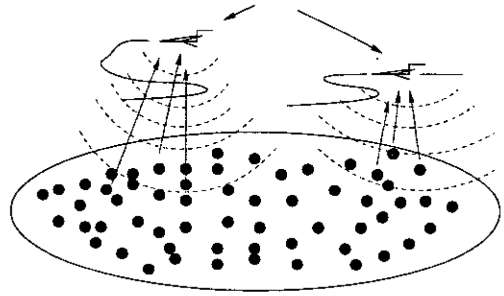

Fig. 1. Sensor Network with Mobile Access Points

To test various aspects of SENMA, we have developed an experimental testbed using acoustic transmission. The designed system implements basic features of SENMA such as mobile access point, sensors, MAC between the mobile access point and sensors. It can be used to study multiple problems regarding the SENMA architecture such as the optimal trajectory, height of flight, one-time coverage of interrogator, and the use of multiple interrogators under the performance criteria like throughput and the number of successful transmissions for a given time, etc. The designed testbed uses indoor acoustic transmission between mobile access point and sensors while SENMA was originally considered for RF channel. Although the acoustic channel is not the same as the RF channel, the use of acoustic gives several advantages. First, it makes it possible to build a testbed within a building room. Second, its propagation characteristic is similar to that of RF channel so that the designed testbed can effectively emulate the system using RF channel. Third, the knowledge through this acoustic SENMA testbed gives some guideline for the later design and development of RF SENMA system.

2. SYSTEM ARCHITECTURE

The hardware elements of the overall system are multiple sensor nodes, a mobile robot with a palm top, and a computer communicating with the robot via wireless LAN. The communication channel between the mobile access point and sensors is acoustic in an audible band.

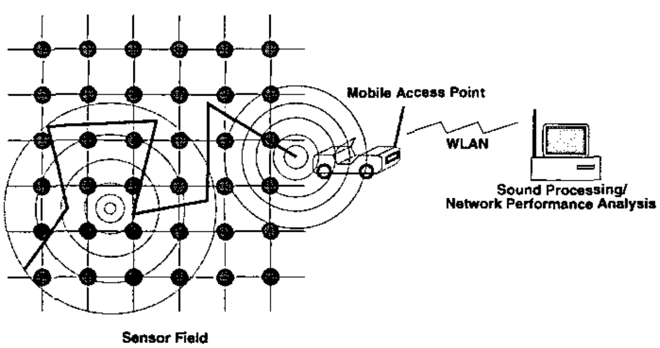

Fig. 2. Overall system configuration

In SENMA, the interrogator and sensors (reachable by it) form a temporary many-to-one network with the interrogator as an access point. So, the system design involves the issues in the design of conventional multiaccess systems like cellular telephony or wireless LAN. However, the different aspect of the SENMA uplink is that the number of nodes can be very large with many correlated sensor measurements due to the scale of the sensor network and the amount of data to be transmitted by each sensor is small. (One packet may be enough.) Hence, it is natural in SENMA to incorporate MAC protocols like the opportunistic ALOHA [4, 5] to utilize multiuser diversity and the information redundancy in sensor data. These MAC protocols usually use the channel state information and the statistic of channel fading.

indoor acoustic characteristics is determined by path loss, reflection, diffusion, and diffraction from walls, ceiling, and floor. The indoor acoustic propagation is characterized by *free* field and *reverberant* field depending on the distance between the sound source and receiver. When the receiver is near the source (usually < 5 ft for small room), the received signal strength drops off 6 dB by each doubling of distance from the source. However, due to the reflection from room surfaces, there is little further signal attenuation with distance away from the source[7]. (This is the fading we want to exploit in SENMA.) Another aspect of indoor acoustics is the sound absorption treatment of room which determines the average level of the reverberant field attenuation. Fig. 3 shows the measurement result of sound atten-

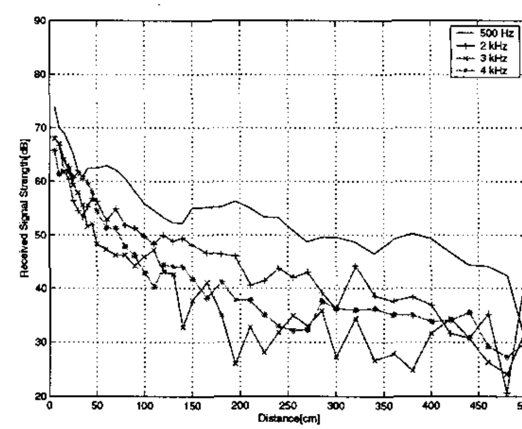

Fig. 3. Received signal strength in a building room (dimension: $29 \times 23 \times 9$ ft^3)

uation in the room where we are going to place the testbed. We used several frequencies to measure the characteristics. For each frequency, the attenuation shows similar trend. It shows a sharp decay near the source and a floor due to reflections. In the fading region, the reflections are added in a constructive or destructive way so that we can observe fading notches with approximately 10 dB depth. By controlling the movement of the interrogator with random displacement by order of $\lambda/4$, we can emulate the effect of both Rician and Rayleigh fading in a room using acoustic channel.

2.2. Transmission Control and Multiple Access

signal simplifies other network functions: It provides the timing synchronization between sensors that are involved in current data retrieval, and serves as a reference signal to estimate the channel state between the mobile access point and sensors.

In the uplink, the designed system can accommodate the conventional ALOHA and opportunistic ALOHA. For the latter, the transmission probability of each sensor is a function of the received beacon strength. With the recent advance in signal processing, one can also consider multi-packet reception (MPR). This scheme requires some mechanism to resolve the simultaneous packets from different nodes. In systems to be deployed in real fields, direct-sequence or frequency hopping spread spectrum or ultra wideband modulation can be used along with the opportunistic ALOHA transmission control to provide MPR capability and low probability of intercept (LPI). In the developed system, we used frequency division multiple access (FDMA) in addition to the opportunistic ALOHA for simplicity. This additional FDMA layer provides several benefits for the test purpose. First, we know if there is a collision between packets explicitly, not by the error of the transmitted information. Second, it is easy to calculate SINR of a particular node since the signal power from each node is available[1] to apply the SINR reception model. Hence, the system can be used to evaluate the throughput for different combinations of MAC and reception models.

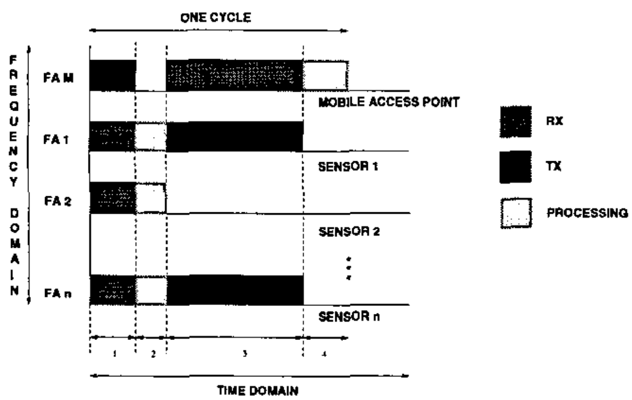

Fig. 4. Transmission control and FDMA structure

The uplink and downlink are further duplexed in frequency domain with the lower band assigned to downlink and the upper band to uplink. (The implementation way of ALOHA itself gives time domain duplexing.) The specific parameters of the design are as follows. The beacon is modulated signals on 500 Hz tone carrying control commands. In the uplink, two band assignments are possible: One is 2 kHz bandwidth from 2 to 4 kHz and the other is 3 kHz bandwidth from 3 to 6 kHz. The band corresponding to harmonics is not assigned to avoid the confusion between actual transmission and the harmonic of fundamental frequency. The frequency difference between two adjacent tones is 15.625 Hz. Two adjacent tones are assigned to each sensor with one representing bit 0 and the other bit 1. Hence, two bands can accommodate 64 and 96 simultaneous transmitting sensors, respectively.

[1]Since the number of frequencies is limited, collision occurs if the same frequency is assigned to two different nodes.

Fig. 4 shows the overall data retrieval procedure. The sensors are initially in the listening mode. The cycle is initiated by the beacon broadcast from the interrogator. Sensors that detect the beacon signal larger than the predefined threshold measure the strength of the beacon and transmit their data at their assigned frequencies according to the probability determined by the beacon signal strength. After the transmission, sensors go back to the listening mode. During the period of sensor transmission, the mobile access point records the sound and processes it to determine which sensors have transmitted and their information. The cycle repeats after the interrogator changes the location.

3. SENSOR AND MOBILE ACCESS POINT

3.1. Mobile Access Point

The mobile access point system consists of a vehicle (mobile access point) and a desktop computer (central control). The vehicle, in charge of collecting data from the sensor field, is a modified remote controlled (R/C) car equipped with a Wi-Fi enabled palm top computer, a speaker, a microphone, and a motion control circuit that connects the palm top and the servos of the R/C car. The desktop communicates with the vehicle through wireless network adapter to control and receive data from the vehicle. After arriving at a position, the mobile access point transmits a beacon signal through the speaker. Sensors that detect the beacon signal measures the beacon signal strength and decide whether to transmit to the mobile access based on the opportunistic ALOHA multiple access scheme. The mobile access point records the sound waveform during the sensor transmission period and delivers the waveform to the desktop via the Wi-Fi link. Further signal processing, detection and statistics gathering are performed at the desktop. Trajectory strategies (random walk for example) and use of multiple interrogators may be tested with the mobile access system.

3.2. Sensor Design

The designed sensors have the functions of sensing, communication, and control. Fig. 5 shows the functional block of the designed sensor. The communication subsystem is composed of receiver (RX) and transmitter (TX). The receiver includes beacon signal detection, received signal strength indicator (RSSI) that is necessary for the opportunistic ALOHA.

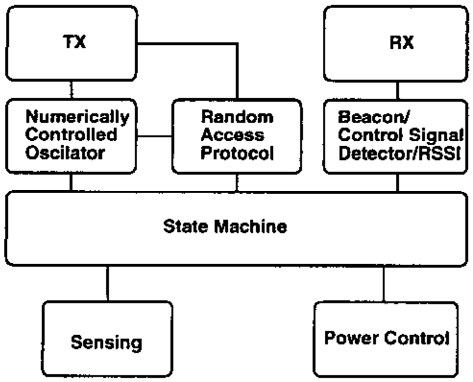

Fig. 5. Sensor functional blocks

The transmitter is composed of a tone generator using numerically controlled oscillator (NCO) and random access protocol. The method we used to implement the random access protocol like the opportunistic ALOHA is very simple and efficient. The different levels of the received beacon strength are mapped to different thresholds that are stored in a ROM table beforehand. A uniform random variable is generated and compared with the threshold determined by the received beacon level. The comparator output gives the decision of transmission. The optimal mapping from channel state to TX probability achieving the maximum throughput is one of the main purposes in our testbed design. (The problem is analytically approached in [5].) A state machine was designed to coordinate the overall sensor operations. Digital functions were designed using VHDL and realized in Altera MAX7000AE CPLD. The analog parts were implemented using commercially available components. Processor with ultra low power consumption is designed for sensor networks using asynchronous VLSI architecture by R. Manohar's group[8]. This processor is considered to be incorporated in later designs. Fig. 6 shows the prototype of the designed sensor.

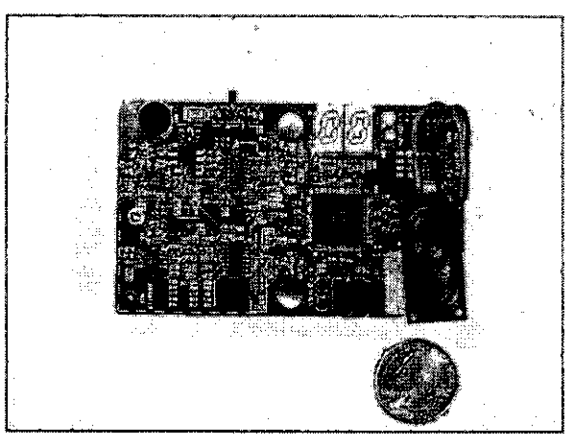

Fig. 6. Sensor prototype design

4. CONCLUSION AND FUTURE WORK

We have developed a testbed for the SENMA architecture using acoustic channel as the initial phase of experimental effort. The developed system contains the main features of SENMA system and can be used to study various factors in SENMA architecture. Experiments are planned to study advanced MAC schemes consisting of user-separation domain[2] and random access in time-domain which utilize both multi-packet reception and multiuser diversity. Fig. 7 shows the configuration of the test setup in a building room. Various experiment regarding SENMA architecture will be performed.[3]

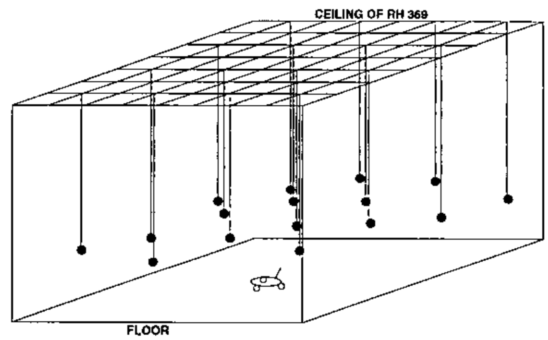

Fig. 7. Test setup

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[2] It means an additional multiaccess scheme such as FDMA, DSSS, FHSS, etc. in addition to the time-domain random access. In the design system, FDMA is used.

[3] The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the offi cial policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.

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