ESTADIUM: A WIRELESS “LIVING LAB” FOR SAFETY AND INFOTAINMENT APPLICATIONS

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ABSTRACT

We propose an application framework that supports safety and security applications and emergency response procedures via integration and inter-operability of sensor networks and wireless LANs. Such a network structure can take advantage of the computational and communication heterogeneity of different devices when the system is carefully designed and optimized.

The proposed wireless network, sensor system, and application framework will be integrated with and support an already functioning 802.11b wireless network in the stadium. This existing network supports the delivery of a variety of multi-media applications - such as on-demand unicast of video clips of game highlights - to fans' portable wireless devices. The resulting dual-use system will be more economical and more capable than two separate systems.

1. INTRODUCTION

Many new system design opportunities have developed over the last few years because of the emergence of a variety of well-established hardware platforms and the increasing sophistication of software tools. One of the most significant new types of systems that can now be designed are those that integrate heterogeneous wireless technologies to support applications that require seamless integration across different hardware platforms. Our goal is the development and deployment of one of these new types of systems. It will integrate many types of sensing, communications, and processing capabilities to support new types of safety, security, and entertainment applications for large sports events.

The base system for our effort will the *eStadium* “Living Lab” that we have developed for Ross Ade football stadium at Purdue University. It currently supports entertainment applications for fans in the stadium on game day. Specifically, it uses an 802.11b network to make the following applications available to fans with portable wireless devices (PDAs and smartphones): unicast streaming of video clips of game highlights; a find-it service for food and drink in the stadium and for local restaurants and hotels; a system to help fans find and exchange messages with other fans with common interests; bios for the players and coaches; etc. Most of these applications can be viewed at:
http://estadium.purdue.edu.

Our eStadium project was the first to offer these applications over a wireless network in a stadium. Since then, 802.11b wireless networks have been deployed in the stadiums/arenas for the San Francisco Giants, Arizona Cardinals, and Dallas Mavericks. Such networks have also been proposed for the support of universal Internet access in Philadelphia (http://www.phila.gov/wireless/) and San Francisco (http://www.sfgov.org/techconnect). The wide availability and ease of deploying this technology thus offers incredible new opportunities for untethered and/or mobile data communications.

Small, low-cost, battery-powered, wireless sensor network technology is a newer technology than 802.11b and is just now emerging from research labs in academia and industry [1]. These small wireless sensors, known as sensor motes, can be distributed over a region to monitor such physical conditions as temperature, sound, light, and pollution and to gather video and images. In addition to these sensors, each mote has a radio transceiver and a small microcontroller. The network topology is self-organized. Data from the sensors is aggregated via a gateway node and further analyzed in a computer.

Some major companies have recently developed different kind of sensor motes with a variety of networking platforms and operating system support. These include Xbow's MICA2 motes and Stargate gateways, Intel's mote 2 platform, Motorola's Zigbee-compliant sensor motes, and Microsoft's SPOT. A variety of applications have been developed based on wireless sensor networks, including habitat monitoring [2], structural monitoring [3], environmental monitoring [4, 5], health monitoring [6], workspace application [7], smart kindergarten [8] and smart agriculture [9]. The largest test to date of networks of these motes has been the ExScal research project that recently completed at Ohio State [10].

Thanks to Cisco, Intel,and Verizon for support.

Our proposed system will network these sensor nodes within a wireless LAN infrastructure. This can improve the efficiency of safety, security, and emergency-response applications in large sports events and other activities in which large crowds are present. These sensors can help emergency operations by locating events of interest and identifying the dangerous areas on an overall map of the situation generated by a large number of sensors. Another benefit of sensor networks is that cooperative analysis of spatially- and temporally-correlated sensor data by the wireless motes will help to reduce false alarms. This type of sensor network application involves all layers of protocol design and cross-layer optimization to obtain better application-level performance. To our knowledge, there are no current security/safety monitoring systems or products for large sports events/venues based on heterogeneous wireless sensor networks of this type.

The remainder of this paper is organized as follows: Section II gives an overview of the eStadium testbed and application development. In Section III, we propose a heterogeneous wireless network platform, including the system architecture and software. Following the system description, we address performance analysis/evaluation issues related to the proposed safety/security application framework. Finally, we conclude with a summary and a discussion of future work.

2. OVERVIEW OF ESTADIUM TESTBED

eStadium is a long-term, large-scale, collaborative project involving the Center for Wireless Systems & Applications (CWSA), Information Technology at Purdue (ITaP), and Purdue Intercollegiate Athletics [11]. The goals of the project include:

- Making Purdue's Ross Ade Stadium the most technologically advanced in intercollegiate athletics;
- Creating a "Living Lab" for research and education in the design and use of wireless networks;
- Identifying and solving problems in the video-on-demand over a wireless network to football fans' PDAs, cell phones, or other portable devices.

eStadium is known as a "Living Lab" because its wireless Access Points (APs) and content/load balancing servers support real users - football fans on game days. Via their PDAs or Smartphones, the fans can access a wide variety of football-related infotainment applications that have been developed by the *eStadium* Vertically-Integrated Project (VIP) team [12, 13]. These applications include: game play-by-play (a list of plays that is updated after each play) up-to-the-moment game statistics, player and coach bios, and a search tool for food concessions, stadium facilities, and local hotels and restaurants.

The most challenging application currently supported by *eStadium* enables fans to view video clips of game highlights [14, 15]. This real-time video distribution system consists of a Location Discovery System (LODS) and an Admission Control Module implemented as a custom plugin under Windows Media Service, which limits the video traffic per AP basis. The client logging plugin was enabled when setting up the *eStadium* streaming publishing point so that the client-perceived video streaming performance can be recorded. Both the LODS and admission control are running as Windows services on the video server which can store the client networking activities (SNMP/syslog) and client connections and streaming details (client receiving logs) into the SQL server database.

Wireless coverage in Ross-Ade Stadium is provided by Cisco Aironet 1200 APs based on IOS software, which is capable of configuring multiple Service Set Identifiers (SSIDs). Each SSID runs on a different Virtual LAN (VLAN) on the same AP, allowing multiple logical networks to coexist in the same physical infrastructure.

Users with PAL accounts can get public IP addresses and can access the Internet. Users without PAL accounts can only get an association with the "estadium" SSID. They will get class C private IP addresses from the *eStadium* DHCP server and can only access the *eStadium* wireless network. The "estadium" network is an open network without any authentication or encryption. Thus, we are able to support both types of users without requiring any modifications to the client devices.

A logical layout of the eStadium's wireless network is shown in Figure 1.

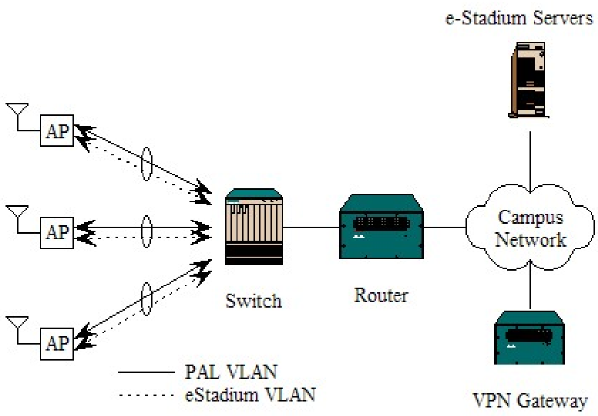

Fig. 1. *eStadium* network architecture

All APs are connected to different switches located on each floor in the stadium, which are then connected to the main router in the stadium. This router routes the traffic differently depending on which VLAN the packet is from. The packets from the PAL VLAN are routed directly to the VPN gateway. The packets from the estadium VLAN are routed to the *eStadium* servers. The *eStadium* servers consist of a DHCP server, two identical content servers, a video server, and a set of load balancing computers to isolate the content servers from possible Denial-of-Service attacks as well as increasing the scalability of the content servers. The packets coming from the PAL VLAN are routed directly to the PAL VPN gateway. Figure 2 gives the details of antenna radiation patterns throughout the Ross-Ade stadium.

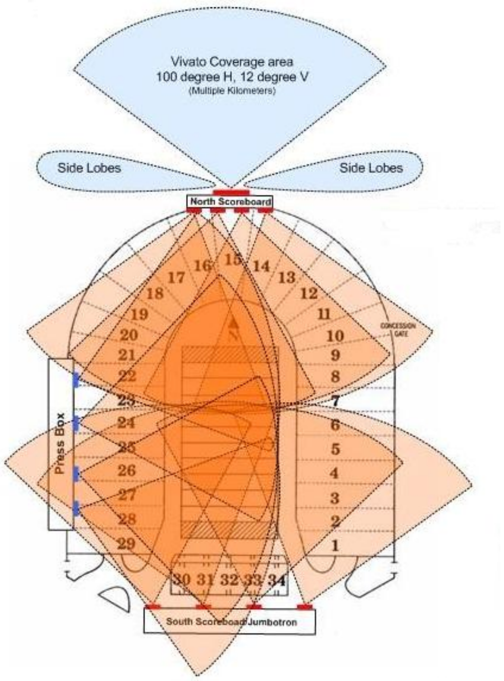

Fig. 2. Wireless infrastructure in the stadium

We are now extending the eStadium wireless infrastructure to a heterogeneous wireless testbed that incorporates a variety of radio platforms. Such a real-life testbed can inspire a wide variety of interactive ubiquitous applications and help evaluate new wireless technologies.

3. OUR PROPOSED HETEROGENEOUS WIRELESS SYSTEM

We plan to leverage the availability of Wi-Fi networks and sensor motes to create a system that uses wireless sensors, mobile wireless devices with custom hardware and software, wireless infrastructure, and custom server-side software. The goal of this system will be to:

- Significantly improve the ability to monitor and secure events in large public places, such as stadiums, arenas, and concert halls.
- Provide a cost-effective, rapidly-deployable system for monitoring and securing outdoor events do not rely on one large structure to house attendees, such as county fairs, art fairs, and outdoor concerts.

3.1. Network Architecture

Our proposed system consists of:

1. one computer serving as a central server
2. PDAs that can be carried by security or event management personnel
3. MICA2 sensor motes to gather information from a variety of sensors and forward sensing data to network gateways
4. Stargates outfitted with web cams to capture video and function as the gateways for MICA2 sensor motes. It also bridges two radio interfaces running at 2.4 GHz and 915 MHz respectively.
5. special purpose hardware and software to integrate the system and support the desired safety/security applications.

This proposed system will have the network architecture shown in Figure 3.

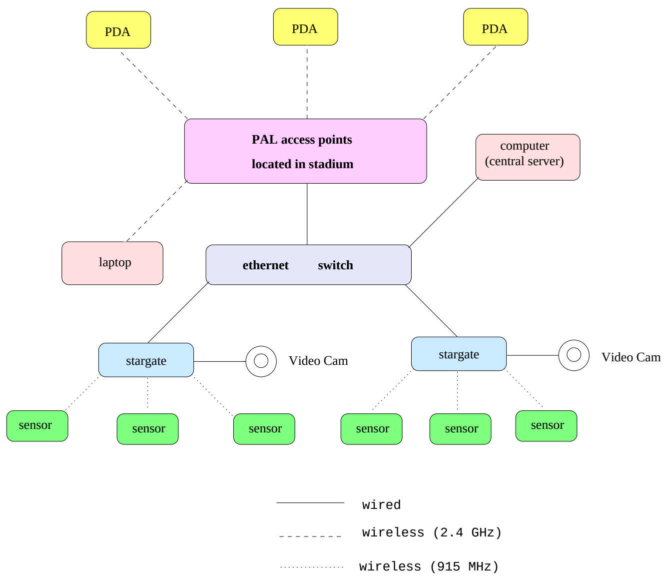

Fig. 3. Network architecture of the proposed security/safety surveillance and response system

In our network system design, Stargates are deployed at fixed locations. Each Stargate is outfitted with a web cam via a USB interface. The video streams from these cameras are then sent to the video distribution service running on the central server so that security and control personnel can view them in real-time from broadcast channels. A sensor mote base station is attached to the Stargate via a 51-pin connector; this mote will collect sensing data from other sensor motes within range and forward the data to the Stargate. We will divide the MICA2 motes into several clusters of sensor nodes, with one Stargate as a clusterhead in each cluster. The concept here is that we can have a variety of sensors on each mote and each mote may have a set of sensors customized for the location it will monitor. These motes are randomly deployed in the venue or throughout a crowd to sense the characteristics of the physical environment, such as sound, temperature, light, vibration, etc.

3.2. Design Considerations and System Architecture

A Stargate is a small-size single board computer with Intel's 400MHz X-Scale processor and 64M SDRAM. It is capable of interfacing directly with MICA2 sensor motes and can bridge the sensor networks to traditional wireless LAN via the PCMCIA or Compact flash cards. Each Stargate is a single board computer running an embedded Linux operating system which provisions enhanced signal processing and communication capabilities and leverages the use of radio heterogeneity.

Each Stargate will be configured to have:

1. one MICA2 sensor mote connected via 51-pin connector as the base station for sensor motes
2. one USB web cam
3. one wired Ethernet interface that will be used to upload video images from its web cam to the central server
4. a wireless compact-flash card which can communicate with the 802.11 wireless access points
5. a PostgreSQL [16] database server with frontend TinyDB [17]
6. an Apache web server which provides a frontend web interface using PHP for real-time information retrieval and display

Figure 4 shows the stargate node that will be used in the proposed system.

The sensors can be of any type, e.g. temperature, light, humidity, magnet, accelerometer, acoustic, smoke, seismic, etc. They are attached to the MICA2 motes, which gather their data and communicate with each other or with stargate (gateway). One challenge here is how to collaboratively distribute and retrieve sensor data. A natural way for accessing

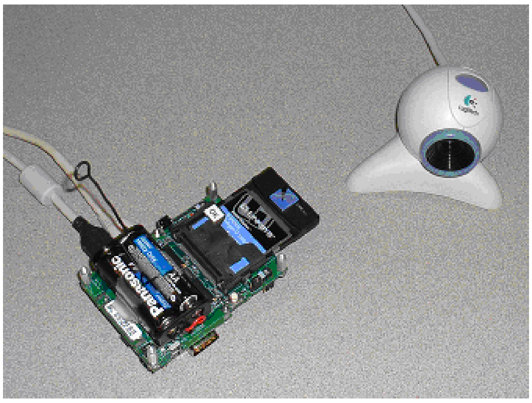

Fig. 4. Stargate demo in the proposed system (outfitted with Mica2 mote, ethernet cable, USB web cam and 802.11b compact flash card)

and processing sensor data is to treat the sensor networks as a distributed database, which is the key concept of TinyDB - a distributed query processor for smart sensors which supports event-based queries. Using this query-based technique for data dissemination has the advantage of reducing the energy cost of transferring data since we can do in-network data aggregation locally instead of sending all raw data to the gateways or central computing units. Another technique that will be helpful in our security applications for further reducing the energy cost is to let low-level sensor nodes periodically sleep and wake up. The S-MAC [18] protocol provides adaptive listening and coordinated sleeping, which efficiently trades off latency and energy savings.

The environmental information gathered by TinyDB will be further stored into a PostgreSQL database system in a round-robin fashion due to the limited storage on the Stargate, i.e. sensing data can be recorded into the database for some period of time, after which the oldest data is going to be replaced by the newest data. Before eliminating the old data, a task is scheduled to run and dump this historical data to the main database server on the central server. This double-database structure enables us to pull out real-time information as well as historical information.

Since each sensor mote has a microcontroller, it will have sufficient processing capability to make a rapid decision and broadcast it to other nodes or the Stargate. This is crucial, because in some delay-sensitive emergency scenarios a response must be generated as soon as possible. Therefore, in our system the sensed data will first be collected and validated on each sensor mote and then forwarded to the Stargate.

The programs running on each sensor mote are written in NesC, based on the TinyOS operation system. Each sensor mote will have a bootloader that allows it to be reprogrammed over-the-air, which adds great flexibility to applications. We, as developers, can then modify the code running on each sensor mote as the environment/venue changes - without having to physically retrieve the sensors from their locations. Reprogramming the sensor node wirelessly is a subtle process that involves the transfer of a program's image (much larger than a data object) over one or more hops without any bit error. *Deluge* [19], capable of rapidly propagating the image throughout the entire network with pipelining, is used to disseminate program image in our application framework.

The main functional units on the central server are:

- Web server with frontend web interface which supports queries on the historical information
- Event detection and emergency response knowledge base
- Video distribution service which supports simultaneous video streaming over different broadcast channels
- Main database server to store all historical data forwarded from Stargates

The video distribution service will set up an independent broadcast channel for each web cam to stream live video images at a pre-specified frame rate. The central server will also provide a web interface to communicate with PDAs through an 802.11b channel. Security and event management personnel can carry the PDAs or smart phones and walk around, all while real-time sensing information is being processed and displayed on the PDA screen for their use. They can also pull out the historical information they might need by specifying the time and and type of data of interest.

The actual implementation of the security/safety applications may be different from case to case, depending on the safety and security requirements of different situations. We store the event/emergency information and response procedures in the knowledge base. Some application-specific service has to be running on the server which monitors and processes different types of real-time sensing data. It can automate the corresponding responses and broadcast the emergency procedures to the PDAs after detecting some potential hazards. The security personnel will then instruct people on how to evacuate if there is an emergency.

The proposed system will thus have the architecture shown in Figure 5.

3.3. Performance Evaluation and Research Issues

The proposed system performance evaluation effort will address the following issues:

- Network Lifetime

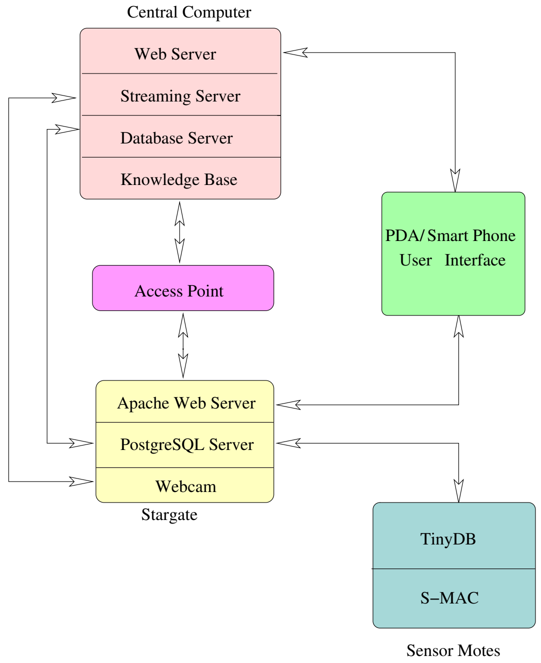

Fig. 5. System architecture of the proposed security/safety surveillance and response system

  Since each sensor mote is battery-powered, what is the maximum network lifetime for the proposed system?

- Effectiveness of Event Detection and Response

  Accuracy and latency are two key metric for surveillance and emergency response. The performance measure for surveillance system includes the event detection miss rate and false alarm rate. What delay would be experienced at the user-level when some critical event happens? Is it tolerable in a particular scenario? How to design the system that can efficiently handle simultaneous detection of multiple events.

- Prioritization of Critical Data

  Communication bandwidth is extremely limited on low-power radios; e.g., sensor data near a disaster site may carry more important information and we should give it priority over other traffic.

- Security

  Security is a major concern for wireless communication systems in general, and even more so in our security surveillance and response system. How do we efficiently verify security credentials at all levels, ranging from the physical to the application layer, is another concern?

4. SUMMARY AND FUTURE WORK

A framework which integrates devices such as sensors, PDAs, Stargates, and computers into a security/safety surveillance and response system was proposed in this paper. The design of such a heterogeneous network prototype considers both low-level components and high-level QoS services. Future work involves validating our proposed system architecture via a detailed performance evaluation. The proposed system will be deployed in the concourse of the Purdue's Ross-Ade Stadium in the summer.

The network architecture we propose in Figure 3 includes 802.11 and generic sensor network interfaces. We plan to add more platforms like ZigBee, Bluetooth, UMTS, EVDO, WiMax into our testbed in the future. There are many meaningful research issues related to multiple radio platforms, including: when to do the vertical handoff and how to do handoff seamlessly; resource managements across the multiple platforms; etc. Such a testbed can thus motivate both theoretical research and technology innovations.

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