Ad-Hoc Wireless Body Area Network for Augmented Cognition Sensors

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Abstract. There is a "spaghetti" of wires when physiological sensors are used for augmented cognition tying a user down to a fixed location. Besides being visually unappealing, there are practical issues created by the "spaghetti" that have a negative impact on the adoption of sensor based augmented cognition technologies. A wireless sensor network can support sensors commonly used in augmented cognition. This paper describes the benefits and issues of implementing an ideal wireless network of physiological sensors using Bluetooth and other related types of networking approaches.

Keywords: *Ad hoc* network, wireless, biosensor, augmented cognition.

1 Introduction

Augmented cognition uses “. . . scientific tools to determine the ‘in real time’ cognitive state of the individual and then adapts the human-system interaction to meet a user’s information processing needs based on this real-time assessment.[1]” The physiological sensors system is the primary tool used to determine the cognitive state of the individual. The authors of this paper will discuss the issues regarding the implementation of a wireless augmented cognition sensor system based on their experience with health monitoring sensors, sensors for augmented cognition and *ad hoc* wireless networks.

Dr. Curtis Ikehara, one of the authors, has recently completed a project for a Waterproof 24/7 Data Recording Biosensor Patch (see Figure 1). The device is a waterproof continuous wear seven day recording biosensor patch to provide physiological vital signs of the wearer and environmental data. The biosensor patch is a thin flat rectangle worn continuously like a bandage for several days and continuously collects vital signs and environmental data while retaining the last seven days of data, like an aircraft black box. The biosensor suite records blood flow (pulse rate), motion, gun fire sound level, skin temperature and ambient temperature. Data from different biosensor patches, individually or in combination, can be used to assess a variety of conditions. The biosensor patch will allow the detection of injury onset and shock while allowing the assessment of fatigue, environmental stress exposure and explosive ordnance exposure. The biosensor patch uses IRDA communications to control the device and to download data.

D.D. Schmorrow, L.M. Reeves (Eds.): Augmented Cognition, HCII 2007, LNAI 4565, pp. 38–46, 2007.

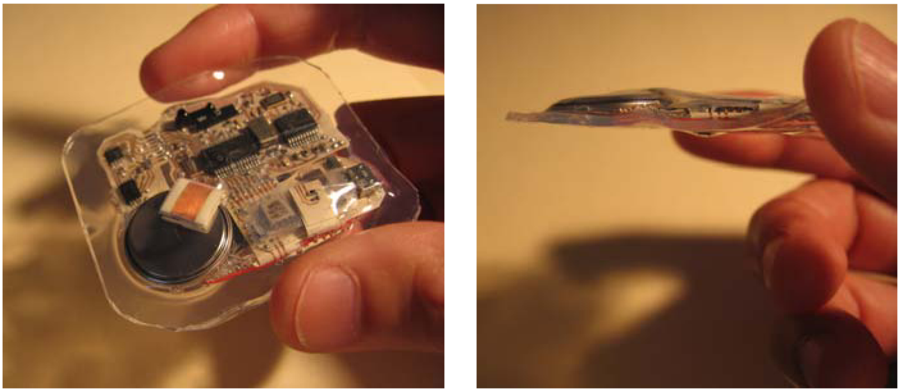

Fig. 1. Two perspective views of the Waterproof 24/7 Data Recording Biosensor Patch

Dr. Edoardo Biagioni, one of the authors, is an associate professor in the department of Information and Computer Sciences at the University of Hawaii at Manoa. His research interests include networking protocols, particularly routing and data transfer protocols for wireless sensor networks and for wireless ad-hoc networks. In 2000-2003 he was co-PI on a DARPA grant, "PODS: A Remote Ecological Micro-Sensor Network"[2], designed to collect information to aid in the preservation of endangered plant species. He has worked on the design and development of a wireless sensor network designed for the long-term study of rare and endangered plant species. These species are monitored in their environment via high-resolution cameras and temperature, rainfall, wind, and solar radiation sensors. Sensor units are part of a large network, the largest deployment having at least 60 nodes. The nodes consume very little power and can operate from batteries for multiple months, and indefinitely long from solar panels. The network uses specialized routing algorithms over 802.11 (adapted to run over Bluetooth, but not tested in the field) to allow communication beyond the range of any individual transmitter. Sensor units exploit transmission path redundancy to compensate for network transmission problems using the wireless routing protocol Multipath On-demand Routing (MOR) [3], which computes multiple optimal routes to avoid depleting the energy at any given node, to recover faster from interference, and to obtain overall higher performance. Other protocols developed as part of this project include Geometric Routing, which scales to large networks, and Lusus, which is useful for networks made up of very simple nodes.

Dr. Martha Crosby, one of the authors, has worked for decades evaluating cognitive performance with a large variety of techniques. She has extensive expertise in the development and use of eye tracking as an indicator of cognitive states and performance. Recently, she has been doing research with Dr. Ikehara on the use of low cost physiological sensors to assess cognitive performance [4], [5], [6], [7].

2 The Ideal Physiological Sensor Network

The ideal physiological sensor network would have a sensor suite so comfortable that the user can wear it for long periods without being tied to a location. The modules would be light weight, low power, low cost and operate under various environmental conditions. The system would support a large number of sensors, would automatically add new sensor modules, would allow for sensor modules with different data characteristics, and would not interfere with nearby users with a similar sensor system or with other electronic devices. Sensor modules would have on-board processing and memory to: extract relevant data using signal processing, perform data compression to reduce the data transmitted, store data if re-transmission is required, time stamp the data, and perform diagnostics to alert the data collection system of problems. The sensor modules would exceed the data transmission requirements, correct for data transmission problems, tolerate sensor module faults, and have an operation time exceeding mission time. Also, the sensor suite would be easy to interface with standard computer equipment, have data encryption and have low detect ability beyond a desired distance to improve security for both the data and the wearer.

The previous paragraph paraphrases some of the characteristics of a 2006 Small Business Innovative Research (SBIR) request, OSD06-H01, for a Bidirectional Inductive On-body Network (BIONET) for Warfighter Physiological Status Monitoring (WPSM). The paragraph also includes characteristics that would be ideal for an augmented cognition physiological sensor suite. The wireless networked health monitoring physiological sensor suite will be coming in the near future. There will be many benefits for an augmented cognition sensor suite that can be compatible with this new wireless health monitoring technology, but there are several issues that need to be addressed.

2.1 Human Factors – "So Comfortable That the User Can Wear It for Long Periods"

Having a comfortable wireless sensor network (WSN) that the user voluntarily wears throughout the work day has many advantages. A few of the advantages are described in this paragraph. First, placement and calibration of the WSN is done once per day, instead of every time the user operates the augmented cognition enabled systems (ACE). The repetitive placement and calibration of the WSN is a major impediment to wider use of the ACE system. Second, knowing the user's cognitive state before using the ACE system allows the ACE system to compensate for pre-existing conditions, such as a racing heart rate caused by running back from lunch. The ACE system would know that heart rate will soon drop and stabilize. Third, knowing the user's cognitive state after performing work will allow the determination of how long a user takes to mentally recover from the previous cognitive task and when the user will be ready to continue working. Fourth, the user can move around and work at several different types of ACE work stations without having to plug into each of the separate stations.

One of the human factors lessons learned by Dr. Ikehara when he was developing the health monitoring biosensor patch was that for the user, a thin large sensor is more desirable than a small and thick sensor. Subjects using the thin sensor, which is approximately 2.5 inches square (65x65mm) commented that after application they couldn't feel it. Where the small 1.25 inches square (30x30mm) sensor was felt and interacted with clothing more. The thin sensor also flexed better with the skin and did not protrude.

The aesthetics would also make the WSN more wearable. One subject who wore the biosensor patch would not wear it again unless the color was blended into the skin so that it wouldn't draw so much attention.

2.2 "Light Weight, Low Power, Low Cost and Operate Under Various Environmental Conditions"

A light weight WSN improves user comfort and allows for multiple sensors to be comfortably worn, but there are several factors that contribute to a sensor's weight. Among the major contributing factors are the size of the power source required for the desired operational duration, the fabricated weight of the electronics and the weight of the encapsulating medium. Low power electronics is desired since less power consumed means longer operational life, a lighter weight battery or the potential for alternate power sources. With very low power electronics, it becomes possible to use alternate power sources including a Peltier device to convert body heat into electricity or a piezoelectric device to convert body motion into electricity [9]. Using the human body as a power source would allow the augmented cognition sensor system to operate for indefinite periods.

To have a low cost augmented cognition sensor system, one approach would be to make the augmented cognition sensor system compatible with mass manufactured health sensor networks. A separately designed augmented cognition sensor network is likely to be more expensive since it will not benefit from the cost saving obtained from large scale production.

The augmented cognition sensor system should operate under various environmental conditions. Environmental conditions fall into two general classes: external factors and conditions that are related to the device as applied to the user's skin. External factors include weather (e.g., water, sun & heat) and chafing (e.g., clothing, carried equipment or between moving body parts). Skin related conditions include skin motion caused by flexing muscles, perspiration, itching and body hair. To address these issues, Dr. Ikehara's biosensor patch encapsulated the electronics using medical grade silicone to repel external factors and medical grade adhesive with perspiration channels. The device was placed on areas of the skin with minimal hair and away from flexing muscles. With improved sensor technology, the sensors could be part of the clothing or a cap, but would still need to operate in various environmental conditions.

2.3 Network Issues

The ideal physiological sensor network should support a large number of sensors, should automatically add new sensor modules, should allow for sensor modules with different data characteristics, and should not interfere with nearby users with a similar sensor system or with other electronic devices. Interference avoidance is accomplished by using low power devices (which also helps reduce energy requirements) and by operating them in a frequency range where they are unlikely to interfere.

Bluetooth is particularly suitable since some Bluetooth devices can transmit as little as 1mW of RF power, and the RF is in the 2.4GHz worldwide ISM band, the same frequency as used by microwave ovens. Bluetooth also uses frequency-hopping, which lessens the likelihood of interference from other devices. Bluetooth is a general-purpose protocol which can support a variety of communication schemes, including those needed by most existing physiological sensors. While unintended communication among Bluetooth nodes can happen, this can be avoided with proper node configuration and programming. The major constraint concerns the maximum data rate, which is limited to anywhere between 700Kb/s and a theoretical maximum of 3Mb/s depending on the version of Bluetooth. In addition, Bluetooth requires a moderate duty cycle, which has higher power consumption than lower-duty cycle technology. Finally, a Bluetooth master device is limited to communicating with at most seven slave devices at any given time, though standards are under development to override this limitation. Overall, Bluetooth provides good quality of service and low data latency.

Two other technologies suitable for use in physiological sensor networks are Zigbee (based on IEEE 802.15.4) and 802.11/WiFi. While some long-distance sensor networks employ 802.11/WiFi, its relative bulk, high power, and high latency makes it unsuitable for physiological sensor networks in spite of its higher overall throughput. In contrast, Zigbee was designed specifically for wireless sensor networks. Zigbee typically uses more power than Bluetooth but can have lower duty cycles, leading to lower overall power consumption. In addition, Zigbee typically has longer range than low-power Bluetooth, allowing communication across a room and at least part way across a building. Finally, Zigbee networks have low data latency and can have up to 65,000 nodes. Golmie, Cypher and Rebala [10] when using Zigbee for ECG found a goodput rate of approximately 50% for 1 to 3 channels of ECG data declining to 5% for 16 channels of ECG data. Bluetooth may be a better choice given the higher data rate requirements of multi-channel electroencephalogram (EEG) data.

Table 1. Salient properties of the three technologies (Bluetooth, Zigbee & WiFi)

	Bluetooth [11], [12], [13], [14], [15]	Zigbee [10], [11]	WiFi® (WLAN) [14], [15]
IEEE Std	802.15.1	802.15.4	802.11
Modulation	FHSS	DSSS	DSSS/OFDM
Frequency	2.4 GHz	2.4 GHz	2.4 GHz / 5GHz
Channels	79 frequencies	16	11
Maximum network speed	3 Mbit/s	250 kbit/s	54Mbps
Range	10 or 100 meters	10-100 meters	50-150 meters
Security	Three security modes	Three security modes	WPA and WPA2 encryption
Approximate Cost	$3	$3	$9
Power Range	0.3-350ma	Can last for years	480-700ma

It is important to recognize that although health monitoring sensors and augmented cognition sensors overlap in function, there are several types of augmented cognition sensors that fall outside of health sensor data requirements. Both health and augmented cognition measure heart rate, heart rate variability, electrocardiogram (EKG/ECG), temperature, blood oxygen, and respiration [16]. Sensors more specific to augmented cognition include: EEG [17], [18], electromyogram (EMG), galvanic skin response (GSR) [16], eye movement and body acceleration [19].

During the normal course of the day health monitoring sensors do not have a high sensor data rate. Although photoplethysmography data is sampled at 16 Hz (i.e., blood flow light sensor), the derived heart rate can be recorded once per minute, while other sensors may need to be recorded less frequently. During intensive care, the data sampling rate for an EKG can be in the 512 Hz range with an accuracy of 12 bits [20]. That would be a 32 times increase in data over the previous sample rate of 16 Hz used to collect heart rate. Augmented cognition sensors like EEG would require more channel capacity given that the sensor uses 128 channels, sampled at 1000 Hz, with 16 bits of accuracy, for a total of about two megabits per second [17]. he previous comparison of EKG and EEG show that health and augmented cognition sensors can have significantly different requirements.

Intermediate Wireless Solutions. Current wireless solutions connect physiological sensors to a single radio frequency wireless transmitter. The signal is received by a nearby device that is connected to a computer. Problems occur when there is another transmitter causing interference, the user moves out of range of the receiver, or ambient electrical noise causes data loss. Also, since the transmission is unidirectional, when a transmission error occurs, there is no method to request retransmission of the data. Another intermediate approach is to use IEEE 802.11/WiFi to transmit the data to an internet-connected access point. Since data delivery time is not guaranteed, sensor synchronization or time stamping is required. Data from multiple sources will need to be synchronized. This occurs even with wire based data collections using the internet [21]. The TCP/IP protocol is most efficient for large blocks of data and much less efficient when transmitting small amounts of data. The latency between data collection and data storage can exceed the system response requirements. Attempts to improve efficiency by collecting large amounts of data before transmitting can further increase latency, whereas using timestamps can substantially increase throughput requirements.

The augmented cognition sensor suite that transmits unprocessed data is likely to tax the health monitoring sensor network, if not overload it with too much data. For the augmented cognition sensor to work within the health monitoring sensor network, it is likely that the data needs to be heavily preprocessed and transmission of the results should be compressed to reduce transmitted data. That would mean that the sensor module may require digital signal processing components to facilitate the signal analysis and data compression.

The augmented cognition sensors create high channel capacity demands on the wireless sensor network. This suggests Bluetooth may be a better choice than Zigbee given the higher data rate requirements of multi-channel EEG data.

Degradation in performance of personal area networks (PAN) can occur because of signal noise and interference from another similar PAN operating nearby. Also, the user may be wearing a wireless health monitoring network that may interfere with the augmented cognition wireless network. Should the augmented cognition sensor network be independent of the health monitoring sensor, it should not interfere with the health monitoring sensor network, since the user's health data should have priority.

Each of the standard wireless approaches, Bluetooth, Zigbee, or WiFi, has its problems. It is likely that a modification of one of the approaches will be necessary. The table below lists some of the issues that need to be considered if a modification or new network protocol is developed assuming all sensor nodes have processing capacity and memory for temporary data storage.

Table 2. New wireless network protocol considerations

How do the sensor network nodes identify themselves as belonging to a user?
How many sensor nodes can be handled?
How is self-diagnosis performed and how is a fault reported?
How do the sensor network nodes communicate with the ACE system?
How will data security be handled?
Initialization of the sensor network How do sensors initialize in the network? How to re-establish communications after a break in communications. How to identify missing or faulty sensors. How are new sensor nodes added to or removed from the system?
Data What is the minimum quality of service? What type of pre-processing of the data can occur at the node? How is data compression implemented? How to synchronize or timestamp all data. How to prioritize data transmission. How to change sensor data transmission rates on demand.
Data loss Retransmission of data protocol
How does a node break communications if it decides to power down.

An *ad hoc* network with the appropriate multi-hop transport protocol and redundant wireless nodes can have redundant communication pathways to the nearest wireless node of the ACE system [2], [3]. With low cost sensor nodes, increasing the number of redundant nodes can create a more robust communications network and provide redundant sensor nodes that can take over the function of a faulty sensor node and improve the overall reliability of the augmented cognition sensor system.

2.4 Additional Network Benefits

The sensor network itself could be used to detect body motion of the user such as appendage movement and the position of the user in a room. To detect body motion, it may be possible to use changing transmission signal strength or the travel time of radio signals from the sensors placed on the user, though both of these techniques suffer in varying degrees from reflections (e.g. from walls and furniture) and self-interference of the radio signal.

3 Conclusion

Wireless sensor networks for health monitoring are almost certain to appear in the next few years. Whether the augmented cognition sensor network is integrated into the health monitoring system or is a separate system, going wireless will be part of the future of augmented cognition.

This paper discussed the benefits and issues relating to an ideal wireless augmented cognition data acquisition sensor system. The benefits of the ideal system will ultimately result in improved user task performance and increase satisfaction with task performance.

Acknowledgements. We thank the Hawaii Technology Development Venture, a project of the Pacific International Center for High Technology Research and funded by the Office of Naval Research for funding the Waterproof 24/7 Data Recording Biosensor Patch. We also thank the Defense Advanced Research Projects Agency (DARPA) SensIT program for funding the Pods project.

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