System Architecture of Wireless Body Sensor Networks

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Abstract— **Wireless Body Sensor Networks (WBSNs) emerged as a design solution of choice for a number of wearable and ubiquitous monitoring applications. Although useful as stand alone monitoring systems, full potential of WBSNs might be explored by integrating individual on-body systems into hierarchical real-time systems to support unobtrusive ubiquitous applications with intermittent communication. However, resource constrains of the lowest levels of the system architecture demand careful system design and specific trade offs in the WBSN design space. Typical issues include proper design of the wireless communication system, buffering, and real-time latency. These issues are application dependent and critically influence system performance and user acceptance. This paper presents system architecture of the hierarchical wireless body sensor networks and design issues in the WBSN design space.**

I. INTRODUCTION

Wireless Body Sensor Networks (WBSN) represent a special case of Wireless Body Area Networks (WBAN) with great potential for continuous monitoring in ambulatory settings, early detection of abnormal conditions, wellness monitoring, and supervised rehabilitation [1], [2]. The advances in WBAN technologies are driven by the developments in wearable and ubiquitous computing, as they share the same ultimate design goals: minimization of weight and size, portability, unobtrusiveness, ubiquitous connectivity, reliability, and seamless system integration. The concept is particularly important for emerging implantable sensors [3].

WBSN based system may provide real-time warning, guidance, and computer assisted rehabilitation and supervision [4][5][6]. In addition, continuous monitoring provides significantly larger data collection that can revolutionize diagnostic procedure and wellness management. Larger data collections may provide personalized and statistically significant indication of short term changes and long term trends. Long term monitoring of trends may provide detection of early signs of deterioration of user's health. For computer assisted rehabilitation applications long term monitoring may indicate progress and guide computer assisted procedures.

To facilitate prolonged monitoring and user's convenience systems must provide unobtrusive operation with minimum power consumption. Power consumption demands minimum size and weight of battery, which mostly determines overall size and weight of the sensors and therefore user's convenience.

Power efficient operation of a WBSN system requires a careful design that takes into consideration application requirements, such as average application data bandwidth, maximum required data bandwidth and latency, need for alerts, etc. User's acceptance will critically depend on trade-off between application requirements.

Application requirements must be carefully matched with the implementation technology. For example, minimum latency and application bandwidth determines the type of wireless interface [7]. Typical implementations include Bluetooth implementation for low-latency applications [8][9], ZigBee for low power applications [10], and application specific very low power applications, such as pacemakers. Illustration of the system design space of WBAN communication system is provided in Fig. 3 and described in Section III. High communication bandwidth reduces maximum latency at the price of increased power consumption that reduces system operation time before battery replacement or recharging.

In this paper we present a typical multi-tier system architecture of WBAN systems, and describe system design space and critical design parameters for proactive systems designed to generate alerts and warnings in real-time.

II. SYSTEM ARCHITECTURE

The most efficient WBAN organization for real-time processing is hierarchical multi-tier organization [4] as presented in Fig. 1. A typical WBAN system integrates several miniature sensor platforms located on the body as tiny intelligent patches, integrated into clothing, implanted below the skin or embedded deeply in tissues. Each sensor platform features one or more physiological sensors, such as motion sensors, electrocardiograms (ECG), SpO2, breathing sensors, blood pressure, electromyograms (EMG), electroencephalograms (EEG), and biochemical sensors (e.g. blood glucose sensors). Sensors could be wired to the platform or reside on the same sensor platform.

Optimal system organization is hierarchical with processing and communication distributed along several levels of hierarchy. Typical systems consume an order of magnitude more power for communication than for on-sensor processing. Therefore, real-time systems should use on-sensor processing whenever limited processing resources of the sensor platform allow. A complete hierarchy of the WBSN is presented in Fig. 1 and described below.

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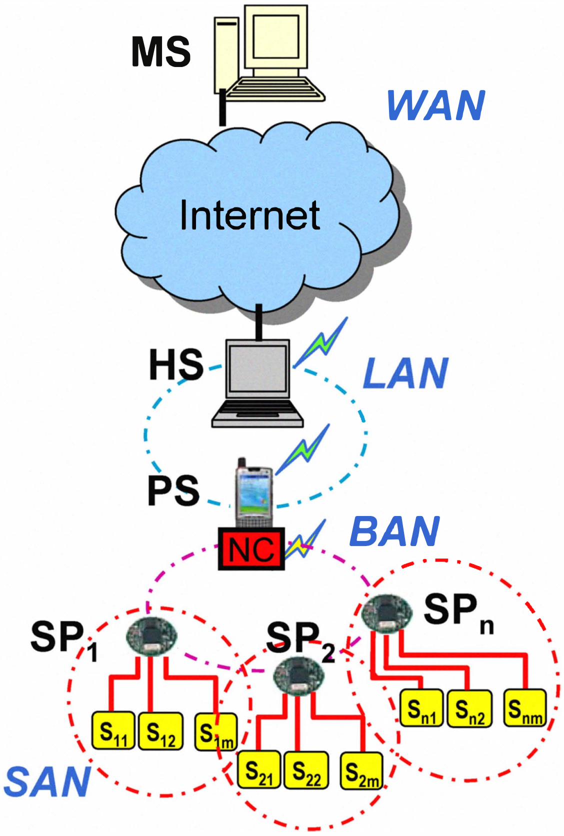

Fig. 1 Hierarchical multi-tier organization of ubiquitous WBAN systems.

A. Network hierarchy

WBAN systems implement several levels of networks:

- *Sensor Area Network (SAN)* integrates several sensors S_{ij} to a single sensor platform SP_i using wired or wireless interface (e.g. implanted sensors).
- *Body Area Network (BAN)* integrates sensor platforms (SP_i) into a single monitoring system controlled by the *Personal Server (PS)*. The personal server also serves as a *Network Controller (NC)*. The BAN communication can be wired in clothing 0 or implemented using short range wireless communication.
- *Local Area Network (LAN)* might be used to integrate sensors or BANs and connect them to the *Home Server (HS)*.
- *Wide Area Network (WAN)* integrates multiple monitoring systems, typically implemented through a cellular network. Ubiquitous monitoring systems rely on WAN for connectivity, using LAN communication only for power efficient communication, when available.

B. Sensor platform architecture

Sensor platforms serve as signal acquisition, processing and communication platforms. Each sensor platform controls one or more sensors, and generates streams of raw data or processed events for each sensor.

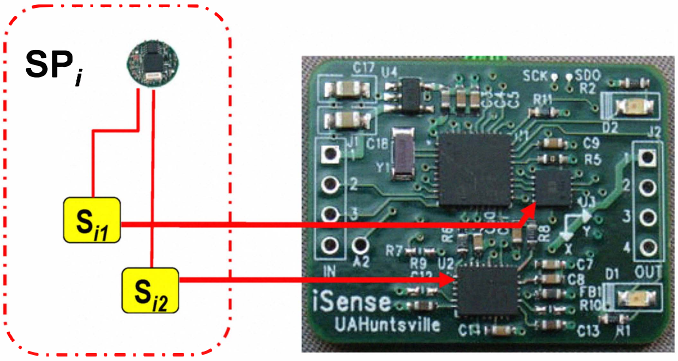

Fig. 2 An example of the sensor platform; inertial sensor platform *iSense* with two sensors: accelerometer (S_{i1}) and gyroscope (S_{i2}).

An example of an inertial sensor platform is presented in Fig. 2. Sensor platform iSense 0 integrates a 3-axis accelerometer (S_{i1}) and two axis gyroscope (S_{i2}) for real-time detection of sensor's position and activity. The personal server communicates with a set of on-body sensors through a serial I2C bus.

III. DISCUSSION

Power efficient operation of a WBAN system requires a careful design that takes into consideration application requirements, such as average application data bandwidth, maximum required data bandwidth and latency, need for alerts, etc. Application requirements must be carefully matched with the implementation technology. For example, minimum latency and application bandwidth determines the type of wireless interface 0. Typical implementations include Bluetooth implementation for low-latency applications, such as real-time control of Avatars in virtual space [9]. Illustration of the system design space is provided in Fig. 3.

The most widely used currently commercially available WBAN technologies include Bluetooth [8] and ZigBee [10]. Bluetooth is a mature technology, already integrated in many computers, laptops, smart phones and Personal Digital Assistant (PDA) devices. Wibree is a low power version of Bluetooth that is well suited for personal WBAN monitoring applications.

ZigBee is an emerging wireless standard for low data rate, very low-power applications, with potential applications in home automation, industrial control, and personal health care [4]. Other emerging wireless technologies, such as Ultra Wide Band (UWB) and Wireless USB, target high bandwidth applications. UWB provides unique location capabilities that might be of interest for some health monitoring application. UWB technology is characterized by asymmetric requirement for receivers and transmitters. As a result a low power sensor can be implemented with transmitter only wireless interface, as represented by the span of UWB block in Fig. 3. On the other side of the design spectrum, MEMS resonators offer extremely low power consumption. However, they provide less precise frequency.

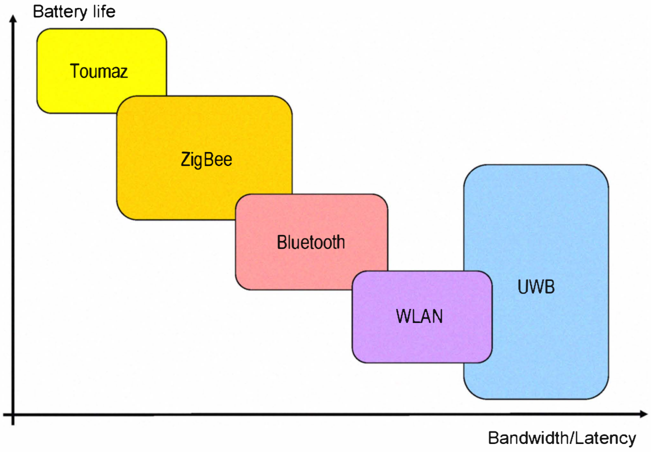

Fig. 3 Design space of the WBAN communication system

Another approach to power optimization is implementation of application specific processors with optimized functions implemented in hardware. A typical example of the new generation of ASICs designed specifically for WBAN with hardware implementation of the protocol stack is Sensium from Toumaz [11].

Critical parameters in the system design are described as follows:

- *Average communication bandwidth* influences the active communication time of wireless controllers and therefore the duty cycle of the system.
- *Maximum communication bandwidth* is parameter critical for bursts of urgent messages, and affects the maximum latency for data transmissions.
- *Maximum power supply current* determines the type, size, and weight of the battery. Maximum current is usually required during transmission. Typical values for different protocols are presented in Table I. It is obvious that some protocols, such as WLAN, although very efficient while active require significant maximum current which determines the type of battery that can be used. A very low power systems can use printable battery technology, which significantly improves user's convenience; however, with a limited power density, peak current, and temperature range [11].
- *Active power* determines the type, size and weight of the battery, as well as the battery life.
- *Standby power* determines the maximum battery life, as a function of the system duty cycle.
- *Communication setup time* is a protocol-related timing parameter that represents time necessary to (re)establish a connection between nodes or a node and a gateway 0.
- *Communication startup time* represents the overhead and determines the efficiency of individual transmissions
- *Asymmetric Receive/Transmit power requirements* of some wireless technologies (e.g. UWB) may influence system organization.
- *Standards based communication technology* influences the system interoperability and application development time.
- *Protocol stack size and processing requirements* determine memory and processor power requirements of the wireless sensor platform.
- *Processing power* of the sensor platform determines type of processing and event detection that can be processed on the platform, as well as power efficiency.

TABLE I

TOTAL POWER AND ENERGY/BIT OF THE TYPICAL WIRELESS TECHNOLOGIES

	Active power [mW]	Power/bit [µJ]
Toumaz	6	180
ZigBee	66	264
Bluetooth	240	333
WiFi (802.11g)	1300	24

On-sensor processing significantly improves system robustness and power efficiency. Wireless transfer typically requires at least an order of magnitude larger power than processing. In addition, on-sensor processing significantly reduces the amount of data that should be transmitted to the upper level of hierarchy. As an example, transferring raw ECG signal requires:

$$\begin{aligned} BW_{raw} &= [1..3]\ \text{(channels)} \cdot [250..500]\ \text{(Hz sampling rate)} \\ &\quad \cdot [12..16]\ \text{(bits/sample)} \\ &= [3{,}000..24{,}000]\ \text{bps} \end{aligned}$$

If the signal is processed on sensor to detect inter beat intervals (RR intervals from R peak events), required bandwidth is reduced to:

$$\begin{aligned} BW_{event} &= [1]\ \text{(channel)} \cdot [0.6..4]\ \text{(events/heart-beats/sec)} \\ &\quad \cdot [16]\ \text{(bits/sample)} \\ &= [9.6..64]\ \text{bps} \end{aligned}$$

Therefore, on-sensor processing is essential for power efficient system operation. However, in the case of critical events (e.g. cardiac arrhythmia), the system should provide raw samples on request of the medical server or the operator.

Measurement of the real-time power consumption [12] allows better profiling of the dynamic power consumption and prediction of the expected battery life. Moreover, power monitoring may provide insights into real-time operation of the device with possible system optimizations by using optimal power down modes. Dynamic power profiling also allows better estimation of the available battery power, as it may significantly depend on the power profile, not only average power consumption. As an example, peak power consumption of smart phones and other devices with WAN interface might be an order of magnitude higher than the average power consumption.

IV. CONCLUSIONS

Wireless body sensor networks represent an emerging integration technology with significant potential to transform clinical and wellness monitoring. The most important applications include unsupervised, continuous, ambulatory health monitoring. Long term monitoring of trends may provide detection of early signs of deterioration of user's health and support for computer assisted rehabilitation.

The main challenge of commercially successful applications is the design of WBAN for extended monitoring of physiological data and real-time detection of events. To achieve that goal a system designer must understand requirements of the application and limitations of the available technology, and simulate worst case application scenarios (e.g. requested bursts of raw signals in the presence of interference and high drop rate, problems with WAN connectivity, etc.). Intermittent WAN communication is still a problem, particularly in rural communities, and the system must be capable of buffering critical events and user notifications during unreliable communication intervals.

Measurement of the real-time power consumption allows better prediction of the expected system operation time and may provide insights into real-time operation of the device with possible system optimizations.

Long-term benefits of the proposed system include promoting healthy lifestyle and seamless integration of data into personal medical records and research databases, which allows knowledge discovery through data mining.

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