A Wearable Point-of-Care System for Home Use That Incorporates Plug-and-Play and Wireless Standards

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***Abstract*—A point-of-care system for continuous health monitoring should be wearable, easy to use, and affordable to promote patient independence and facilitate acceptance of new home healthcare technology. Reconfigurability, interoperability, and scalability are important. Standardization supports these requirements, and encourages an open market where lower product prices result from vendor competition. This paper first discusses candidate standards for wireless communication, plug-and-play device interoperability, and medical information exchange in point-of-care systems. It then addresses the design and implementation of a wearable, plug-and-play system for home care which adopts the IEEE 1073 Medical Information Bus (MIB) standards, and uses Bluetooth as the wireless communication protocol. This standards-based system maximizes user mobility by incorporating a three-level architecture populated by base stations, wearable data loggers, and wearable sensors. Design issues include the implementation of the MIB standards on microcontroller-driven embedded devices, low power consumption, wireless data exchange, and data storage and transmission in a reconfigurable body-area network.**

***Index Terms*—Bluetooth, body area network (BAN), data logger (DL), embedded system, home healthcare, IEEE 1073 Medical Information Bus (MIB), interoperability, mobility, open system, plug-and-play, point-of-care, standards, wearable sensors, wireless communication.**

I. INTRODUCTION

DESKTOP and wearable monitoring systems can collect health data in the home, facilitating disease prediction and diagnosis [1]–[4]. By reducing face-to-face consultations and shortening hospital stays, home care technology can help to compensate for healthcare resource inadequacy (e.g., in rural or inner-city environments [5]), while maintaining or improving care quality [6]–[8].

Despite increases in home care technology availability and application, home care delivery can still be improved through advances in human factors, continuous monitoring, cost-effective wearable devices, and reconfigurable systems [9], [10]. The number of elderly home care service users is increasing [11]; these individuals will likely have difficulty using electronic devices. In addition, chronic problems (which contribute to most deaths and illnesses in the United States [8], [12]) require continuous, long-term monitoring, rather than episodic assessments. Continuous monitoring can also benefit telerehabilitation patients or those recently released from the hospital [13]. For these patients to engage in normal daily activities, point-of-care devices must be unobtrusive and wearable [14]–[16]. Furthermore, multiple sensors per individual can be expected, and these configurations will depend on users' care needs. Wearable systems should, therefore, support dynamic sensor and storage reconfigurability. These plug-and-play features, coupled with security [17], [18], can improve user experiences and device acceptance, increasing demand and lowering prices. When interoperability is supported with consensus standards, vendors can develop specialized components, improving product development efficiency and further lowering costs through market competition. Low-cost, interoperable devices have tremendous potential to address cost and acceptance barriers experienced with current telehealth technology [7], [10].

Recent efforts have addressed constraints like device wearability and networking [1], [9], [12]–[15], [19]–[26], allowing progress in telehomecare [27], [28]. In addition, several groups have developed technology to help devices discover and dynamically interact with nearby devices without the need for user intervention [21], [24], [25], [29]–[34]. Nonetheless, cost and usability issues continue to limit adoption of wearable home care technology. Mature plug-and-play standards are needed that allow users to configure their own systems, and enable companies to compete at the device level, lowering costs and increasing technology acceptance.

This paper presents a system that addresses usability issues [9], where standards are applied for plug-and-play interoperability, reconfigurability, and wireless interdevice communication. Section II addresses plug-and-play device design and summarizes candidate standards for wireless communication and medical information exchange. Section III presents the design of a three-level, wearable point-of-care system that uses the Bluetooth and Medical Information Bus (MIB) standards, enumerating issues that affect MIB implementation on embedded platforms. Section IV evaluates the products from this effort, while Section V addresses technical hurdles and suggests improvements to the MIB standards for application to wearable, wireless devices.

II. BACKGROUND

A. Plug-and-Play Design

"Plug-and-play" has multiple connotations: ease of use, device compatibility between different vendors, and "on-the-fly"

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TABLE I
DRAWBACKS OF WIRELESS STANDARDS WHEN COMPARED WITH BLUETOOTH FOR WEARABLE MONITORING APPLICATIONS

IrDA	Short distance; Only point-to-point communication; Requires line of sight.
IEEE 802.11b	Complex protocols; High price; Interference sensitivity (due to direct sequence spread spectrum technology); Higher power consumption.
HomeRF	Disbanded in 2003.
ZigBee	Limited data rate; Only recent product availability.

scalability and reconfigurability. This requires that one provide physical connectivity and application-level interoperability. The former speaks to reliable and secure data transfer, where a system must detect the presence of a new device and negotiate a communication protocol. Application-level interoperability allows devices to synchronize their operational behavior and working states, understanding each other by means of a common message syntax, data types, encoding rules, and nomenclature. Manufacturers often build systems on top of other standards to achieve universal interoperability. Standards exist for lower layer [30]–[32] and upper layer [24], [25] development, most of which refer to the ISO/OSI seven-layer model [35]. The following two sections address the transport-level (Bluetooth) and application-level (MIB) standards chosen for this development.

B. Wireless Communication

Multiple wireless communication standards exist [36]–[38], each suited to certain applications. Bluetooth, chosen for this project, operates at 2.4 GHz and uses frequency-hopping spread-spectrum technology to prevent eavesdropping and to improve interference immunity. The Bluetooth specification supports 1, 10, and 100 m transmission ranges. It features low complexity, low power consumption, and a reasonable target price ($5 per unit in quantity). Bluetooth offers a point-to-point serial mode as well as a Host Controller Interface mode (used for this effort), whereby one master device can dynamically form a piconet with up to seven active slave devices. Bluetooth also supports plug-and-play operations such as inquiry, connection, disconnection, and *ad hoc* networking. Its specifications make it suitable for wearable monitoring devices. Table I lists the characteristics of alternative wireless standards that prompted the selection of Bluetooth for this effort.

C. Medical Information Exchange and Device Interoperability

National and international organizations work on standards that address upper layer medical information representation and exchange [39]. These standards include Health Level 7 [40], [41], VITAL [41], and DICOM [42]. This project adopted the IEEE 1073 standards for medical device interoperability. This group of standards, also called MIB, was recently renamed the ISO/IEEE 11073 standards (a.k.a. X73) to reflect efforts to internationalize the standards. In this paper, the descriptors "IEEE 1073" and "MIB" are still used to maintain consistency with the standards documentation and source code that support this development. The IEEE 1073 standards provide "interconnection and interoperability of medical devices and computerized healthcare information systems" [29] for acute care in bedside environments. These standards specify seven layers based upon the ISO/OSI model [35]. The MIB technical committee also works with the Health Level 7 working group [40], [41] to promote exchange of medical device data between systems [29]. While developed for bedside devices, MIB defines nearly all of the elements needed to implement plug-and-play wearable monitoring systems, given its full information model, communication model, nomenclature, association control, and service access.

TABLE II
FAMILY OF MIB STANDARDS

P1073.1 provides definitions for information representation and interchange [51, 52].
P1073.2 defines the application profiles which specify protocols and services relevant to the upper three layers of the ISO/OSI reference model [43].
P1073.3 (Transport Profiles) specifies protocols and services for connection and message transport, using existing international standards where possible. This substandard addresses the data link layer, network layer, and transport layer of the ISO/OSI reference model [44, 50].
P1073.4 addresses the cable-connected physical layer [49].

The MIB standards consist of a complex family of substandards organized in an object-oriented framework (see Table II) [29], [33], [43]–[52]. The work in this paper relates primarily to P1073.1 and P1073.2 (see Section III). P1073.1 defines a Domain Information Model and a service model adopted from VITAL. In the "Medical" package inside the Domain Information Model, a hierarchy of objects such as Virtual Medical Devices, channels (objects that hierarchically organize metric objects), and metrics (numerics, sample arrays, etc.) are derived from a virtual medical object base class to represent medical devices and data. The "Persistent-Metric-Store" object in the "Medical" package allows storage and representation of long-term metric data (see Section III). In the "System" package, the medical device system (MDS) object is the abstract model of a medical instrument that provides physiological data. A medical device data language [47], [48] uses vocabulary defined in the Domain Information Model, and both general and specialized virtual models for vital-sign monitoring devices are specified in this data language.

The MIB communication service model is based upon the agent/manager concept in system management, where an agent is a server providing data to its client, a manager. Each agent and manager has a device communication controller (DCC) and a bedside communication controller (BCC), respectively. When two devices attempt to communicate with each other, their DCC and BCC follow five steps: 1) **Local Initialization**: the agent initializes its object attributes and enters a "disconnected" state; 2) **Connection**: the devices set up a physical connection; 3) **Association**: the manager requests an association and the agent responds; 4) **Configuration**: the agent reports its configuration to the manager so the manager can make a copy of this configuration; 5) **Operation**: the agent uploads its data to the manager. To support wireless operation, MIB defines a substandard to pro-

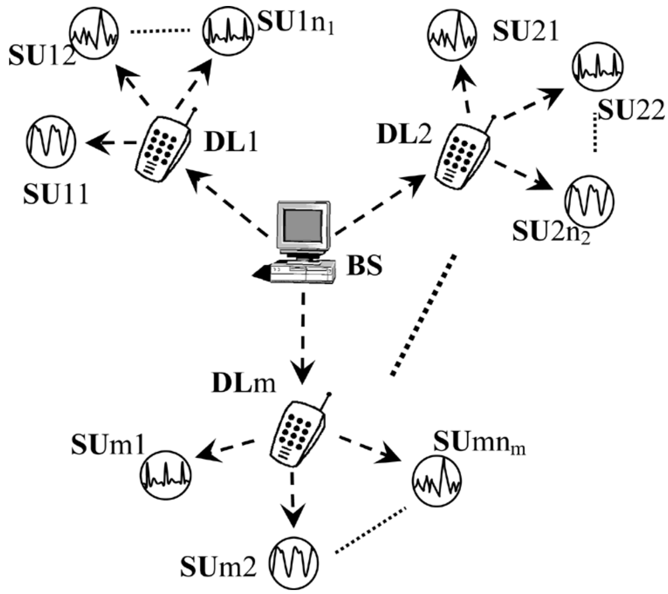

Fig. 1. Horizontal view of a wearable point-of-care system using *ad hoc* scatternet technology.

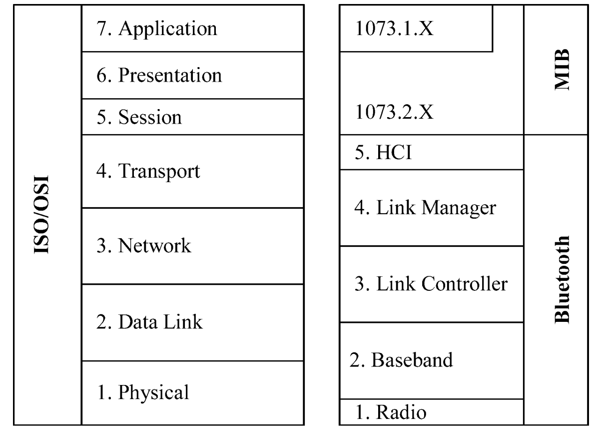

Fig. 2. Vertical depiction of the layered device architecture relative to the ISO/OSI model.

vide connection-oriented services and protocols consistent with the IrDA specification [50].

The MIB committee tailored the plug-and-play VITAL standards to bedside devices. This optimization, specified in P1073.2 [43], 1) reduces message overhead, 2) makes protocol data unit (PDU) encoding and parsing more efficient, and 3) relaxes computational capacity and memory requirements. In the Domain Information Model, data are formalized using Abstract Syntax Notation One (ASN.1), an international standard created to describe the structure of data exchanged between communicating systems. MIB medical device encoding rules follow only a restricted subset of the ASN.1 encoding rules. These medical device encoding rules support encoding/decoding of "canned" messages: PDU templates that are pre-encoded and stored into memory, where fields that need to be efficiently updated during run time are located at fixed offsets.

III. Methods

A. System Layout

As noted earlier, an ambulatory point-of-care system for home use should be wearable, easy to use, and capable of continuous monitoring. This section introduces an MIB-based point-of-care system designed to meet these requirements. Figs. 1 and 2 illustrate the horizontal and vertical views of such a system. Fig. 1 shows the three-level hierarchy comprised of a base station (BS), data loggers (DLs), and sensor units (SUs). One BS would typically be installed in a living area, although a home can contain multiple living areas. A BS and its m connected DLs (for m individuals) form a wireless local area network in this living area. Likewise, each DL_i (for the ith user, $i = 1, 2, \ldots, m$) and its n_i connected SUs form a body area network (BAN). The number of DLs (m) connected with the BS and the number of SUs (n_i) connected with DL_i are both scalable.

A BS receives data from each DL and stores these data for further use. The BS (e.g., an Internet-enabled personal computer) could display technical, physiological, and demographic information. Both SUs and DLs have storage capability and upload data intermittently to make communication more efficient and to improve system mobility. An SU stores acquired data and transmits them to a DL before its memory fills. A DL, which has a much larger memory capacity, can store data for a longer time prior to uploading its data to a BS.

This system is laid out vertically, as shown in Fig. 2. The lower five layers of the Bluetooth stack perform tasks defined in the lower four layers of the ISO/OSI model. Two MIB substandards (P1073.1 and P1073.2) define application-level operations. Detailed information regarding the incorporation of Bluetooth is given in the following subsections.

Note that, unlike traditional *ad hoc* wireless networks, this three-tier topology need not address routing protocols and multicasting. This system uses point-to-point communication between Bluetooth master–slave pairs in different levels, improving overall communication efficiency and avoiding situations such as patient A's DL being asked to route data acquired from patient B's sensors. In this environment, a DL is a mobile storage surrogate for a BS, and a one-to-one mapping exists between DLs and patients.

B. Standards Conformance and the Device Model

When possible, device definitions and interactions in all three levels (see Figs. 1 and 2) conform to P1073.1 and P1073.2 (see Section II). The devices do not conform to the transport profile due to the use of Bluetooth. Within this context, each SU conforms to a particular vital sign device model defined in P1073.1.3.x [47], [48].

Devices are modeled according to the MIB Domain Information Model. First, an SU is modeled as an MDS and works as an agent. Each sensor consists of a Medical Function Unit and the required accompanying MIB objects, where the Medical Function Unit models the circuit and software for physiologic information acquisition. The required MIB objects within a sensor are primarily those defined in the "Medical" package of the Domain Information Model, such as a Virtual Medical Device, channel objects, and Persistent-Metric-Store objects.

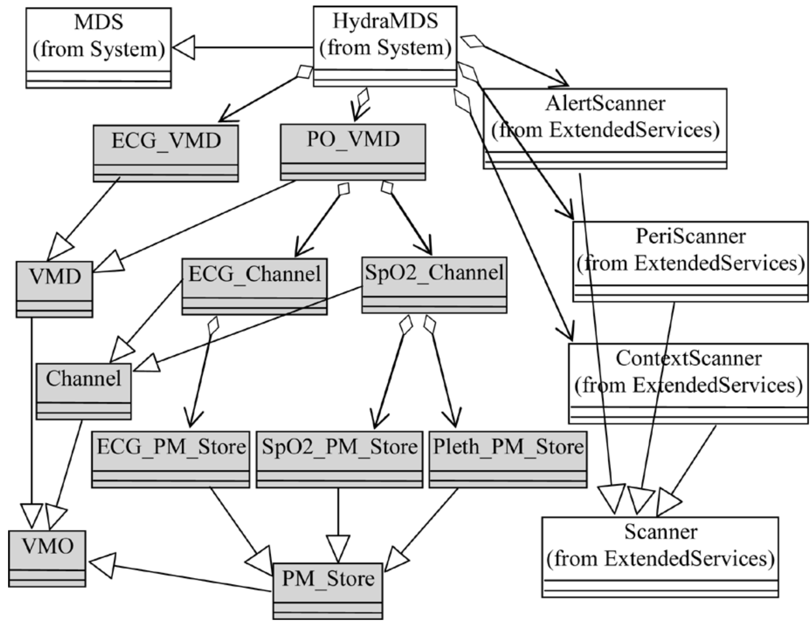

Fig. 3. Object model for an MIB-based DL.

Objects from other packages, like Scanners (objects from the "Extended Service" package that observe object attributes) and DCCs (from the "Communication" package), are also included. A DCC controls communication by interacting with the Bluetooth module.

Second, a BS is modeled as a patient care system (PCS), adopting all application-level services. Fundamentally, a BS consists of a data/device management unit and a BCC, which controls communication over the Bluetooth wireless link. In the agent/manager communication model, a BS works as a manager whose application processes, including an embedded database, deal with data logging, event logging, and device work status.

A DL is both an MDS (agent of the BS) and a PCS (manager for SUs). It has a DCC and a BCC which control communication to the BS and the SUs, respectively, by interacting with their corresponding Bluetooth modules. As a PCS, the containment tree for a DL is mirrored from the configuration of the associated MDSs. Fig. 3 models a possible configuration for a DL. In this instance, the DL is associated with two SUs: a pulse oximeter and an electrocardiograph (ECG). The DL is modeled as a Hydra MDS (it is derived from the MDS base class) at the top of the hierarchy. This Hydra MDS is associated with two Virtual Medical Device objects: the *PulseOx_VMD* and the *ECG_VMD*. Each Virtual Medical Device contains a channel designed to conform to the definition in the draft standards of specific vital sign devices (IEEE P1073.1.3.4 / D3.0 [47] for the pulse oximeter and IEEE P1073.1.3.6 / D6.0 [48] for the ECG). The pulse oximeter channel *SpO2Channel* is associated with two types of Persistent-Metric-Store objects: a numerical Persistent-Metric-Store object stores the blood oxygen saturation percentage, and a real-time sample array Persistent-Metric-Store object contains the photoplethysmographic waveform for each light excitation wavelength. Similarly, the *ECG_Channel* contained in the *ECG_VMD* is associated with a sample array (Persistent-Metric-Store object) that stores the real-time ECG waveform over an extended period.

During practical operation, this containment tree is formed dynamically in the *Configuration* stage after two devices are connected and associated. For example, a DL and a pulse oximeter may have already completed their association steps and entered into normal data operation (the DL's containment tree already includes mirrored images of the pulse oximeter entries). When an ECG SU approaches the DL, the ECG and DL follow the steps to establish a connection and an association (see "Medical Information Exchange and Device Interoperability" in Section II). The ECG then describes its configuration to the DL, which adds this information to its containment tree. The next section describes this interaction in detail. Messages exchanged between devices conform to the MIB standards. Specifically, PDUs involved in device connection, association, configuration, and normal operation are precoded, following the definitions in the MIB application profiles. Most of these PDU templates are adapted from MIB demonstration projects [53].

C. Device Inquiries and Connections

An MIB manager (Bluetooth master, i.e., a BS or a DL), periodically inquires for new devices (MIB agents, a.k.a. Bluetooth slaves), and requests to connect to these newly found devices. This process is illustrated in Fig. 4. An agent can only respond to one connection request at a time, so it addresses the first request it receives and ignores all others. Items 3 and 4 in Fig. 4 accompany horizontal dashed lines, indicating that these steps are not part of the current MIB standard. For DL/SU interactions, the Bluetooth modules maintain the link after an association is established. If the link is broken, the two devices must restart the inquiry, connection, and association process before the SU can upload new data to the DL. Different rules apply to BS/DL interactions, since 1) a user will enter and leave the range of a BS

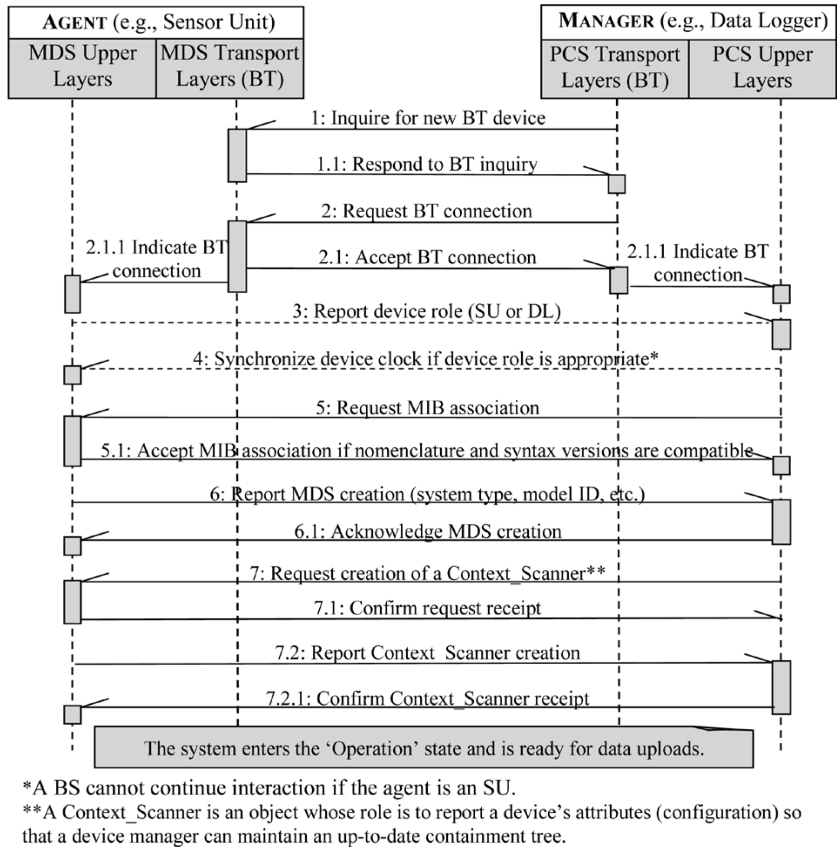

Fig. 4. Interactions between an MIB agent and an MIB manager.

more often than a sensor is added to or removed from a DL, and 2) a DL uploads its data less frequently than an SU because of its larger memory space. A DL accepts a connection request only when its data are ready or nearly ready to upload. Once these data are uploaded, the DL breaks the link to minimize power consumption. This disconnection also promotes system scalability by making room for new DLs and freeing DLs to communicate with other BSs.

D. Implementation Issues

This section addresses issues regarding the implementation of a microcontroller-based, wearable, wireless medical system that attempts to adhere to the MIB standards, including the Domain Information Model, the connection/association steps, and functionality accomplished by each device. However, the implementation did not fully comply with the MIB standards, primarily due to **resource limitations** (memory, computational capacity) on the embedded devices, and the **incorporation of Bluetooth**, which is not currently supported by the MIB standards.

While a limited number of operating systems exist for microcontrollers, no operating system was used on the implemented devices; the additional power and size requirements were not desired (especially at the sensor level). Furthermore, the features of these operating systems are insufficient for practical applications. The design adaptations imposed by these decisions are addressed in the following subsections.

1) PDU Encoding/Parsing: MIB defines most PDUs with fixed lengths and data, which significantly simplifies PDU encoding and parsing. Given the microcontroller's limited computational capability, most of the PDU templates are completely encoded and stored in ROM rather than being encoded "on-the-fly." A PDU template can be copied to RAM when needed. Since changeable fields are located at fixed offsets in a PDU, their values are written at the appropriate offsets after each PDU is copied to RAM. In a device that receives PDUs, expected information can then be directly accessed before the corresponding actions are taken. The system does not require full knowledge of the PDU structure.

Nevertheless, one PDU needs to be constructed dynamically: a DL's Context-Scanner-Creation-Event PDU. Since the number and type of devices associated with the DL may vary, the PDU has to be encoded to report this configuration change to a BS. To address this need, we first code the overhead of this PDU and a set of component attributes for possible SUs (e.g., pulse oximeter, ECG). In the Configuration stage of a DL/BS interaction, the DL copies the PDU overhead and the components for the associated SUs from the ROM to the RAM, then assembles the Context-Scanner-Creation-Event PDU that reflects the current configuration.

2) Data Storage: The system also needs to manage external memory. In both a DL and SU, the external memory space is split into an upper group and a lower group. When one memory group is full, the device uploads those stored data, while placing newly acquired data in the other memory group. In a DL, in which flash memory is used, once data are uploaded to a BS, the microcontroller starts erasing uploaded sectors during available time slots.

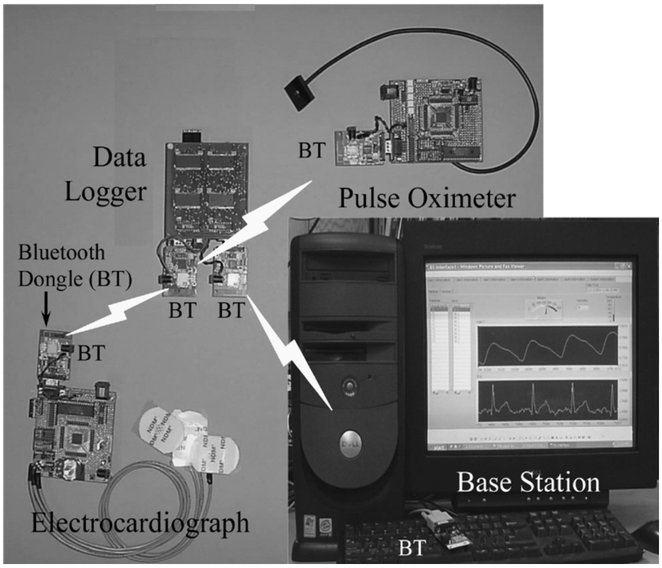

Fig. 5. Demonstration system.

3) Time Stamp: Relative time stamping and synchronization are concerns for an SU and a DL. For a wearable system in a home environment, it is important to know when physiologic data sets are acquired relative to one another, often within fractions of a second. However, physiologic data from separate sensors are uploaded at different times. Connections and disconnections between devices can occur frequently, making synchronization even more difficult. In this system, real-time clocks are used in each DL and SU. When a DL first associates with a BS (as mentioned in Section III), the BS synchronizes the DL relative to a fixed reference (12:00 a.m., January 1, 1904, defined by LabVIEW, the software program used to create the BS interface and functionality). A DL times events relative to this baseline, and synchronizes an SU relative to the baseline during DL/SU associations. An SU real-time clock starts timing at the synchronization time point. Whenever an SU uploads data, it embeds the relative time into the PDU. The DL then uploads these data to a BS without modifying the time stamp. Since all times are relative to the same reference, the BS can interpret time stamps correctly.

IV. Results

The MIB-enabled prototype, a follow-up to previous work [9], [54]–[56], incorporates a BS, a DL, and two SUs that communicate via wireless Bluetooth links (see Fig. 5). This section addresses the prototype hardware and system performance.

A. Prototype Description

In the DL and SUs, a PIC 18F8720 microcontroller interfaces with each Bluetooth module via an RS-232 port. On the BS, the Bluetooth module plugs into a PC serial port. BrightCom Callisto I Bluetooth modules provide DL-to-sensor connectivity at 9.6 kb/s, while Callisto II modules provide BS-to-DL links at 115.2 kb/s. These modules work in Host Controller Interface mode: a master can communicate with multiple slaves.

1) Microcontroller-Based Components: The DL and SUs all use PIC 18F8720 microcontroller development boards, promoting code reuse. The PIC 18F8720 can handle up to 18 prioritized interrupt sources, assisting multitask scheduling. The microcontroller has two programmable universal asynchronous receiver/transmitters, one 10-b, 12-channel analog-to-digital converter, and 2 MB of external memory. These attributes minimize the number of peripheral chips and reduce the device size, weight, cost, and power consumption.

TABLE III
Specifications of Wearable Components

	ECG	Pulse Oximeter	Data Logger
Sample Rate (Hz)	200	50	–
Channel Number	1	4	–
Storage Space (Mbytes)	1	1	16
Storage Time (hours)	~1	~1	Up to 14
Battery Life (hours) Using 4 Alkaline AA Cells	~10	~10	~10
Data Rate (kbit/sec)	9.6	9.6	115.2

The DL consists of a microcontroller board, a memory board, and two Bluetooth boards. The total addressable memory is increased from 2 to 16 MB by expanding the external memory address bus from 20 lines to 23 lines. To guarantee data integrity, nonvolatile flash memory with a high storage density is employed in the DL. Four AM29F032B flash memory chips provide program and data memory in this custom upgrade.

The first sensor, a two-wavelength (red at 660 nm; near-infrared at 940 nm) reflectance pulse oximeter, yields reflectance plethysmograms for calculation of heart rate, blood oxygen saturation, and other parameters. The second sensor, a three-lead ECG, uses the same microcontroller board design as the pulse oximeter sensor.

2) Base Station: The BS (a PC) has a LabVIEW interface [57]. It displays user demographic information, device status, and physiologic data. Information for different users is displayed on different pages. Sample arrays for connected channels are displayed on the screen and saved into data files for follow-up analysis. The BS incorporates algorithms for motion artifact removal and calculation of heart rate and percent oxygen saturation from reflectance sensor data.

LabVIEW's graphical programming method, Graphical-Object-Oriented-Programming (GOOP), accommodates BS configuration "on-the-fly" for associated DLs. Graphical objects can be constructed and deleted by calling GOOP virtual instruments. Here, pulse oximeter and ECG objects are implemented as GOOP classes, and can be dynamically instantiated and destroyed as a DL reports its sensor changes. This achieves the desired system scalability and reconfigurability.

B. Overall System Performance

The system was evaluated for its mobility, network reconfigurability, and data transmission capability: important indexes for the target application environment. Table III summarizes the performance of the wearable devices. Mobility relies on two

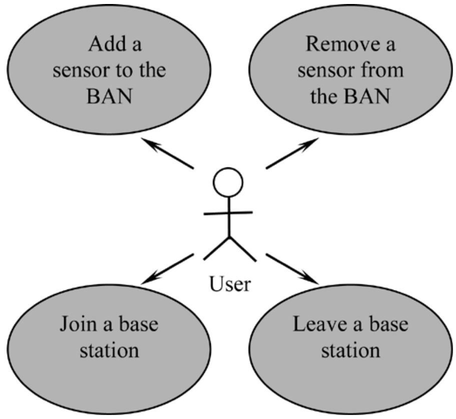

Fig. 6. Use cases for testing the MIB-enabled system.

factors: local device storage and battery life. With a 16-MB memory space, the DL can store up to 14 h of data when receiving data from a sensor with two 10-b analog input channels, each sampling at 50 Hz. It takes about 90 s for the DL to upload these data to the BS at a rate of 115.2 kb/s. The microcontroller and the flash chips have sleep/standby modes and are energy-efficient. When active, the DL consumes about 100 mA at +5 V; it requires much less current in sleep mode.

In the configuration depicted in Fig. 5, the pulse oximeter samples the reflectance data at 50 Hz per channel (four channels), and can store up to 40 min of data before it must upload these data to the DL. The ECG sensor can store up to 50 min of data prior to uploading its data to the DL when it samples at 200 Hz. The upload process takes about 30$\sim$40 s, with an average transfer rate of 9.6 kb/s.

To test the three-level system reconfigurability, use cases requiring plug-and-play connectivity were tested, as illustrated in Fig. 6. When a sensor arrives within or disappears from a DL range, this event can be detected by a DL. The appropriate objects will be dynamically added to or removed from the system and reported to the corresponding BS, which then displays the change. Similarly, a DL can dynamically join or leave a BS without user intervention. The system achieves true "plug-and-play" functionality: its configuration changes immediately, depending on the current monitoring needs of the patient.

In the target environment, where data are transmitted in multiple-packet burst mode within a *store-and-forward* framework, some performance parameters (e.g., transmission delay) are not as critical as they are in a real-time wireless network. The most important index for this system is its performance in a worst-case scenario, when all Bluetooth slaves of a master attempt to upload data to the master simultaneously. Due to the significant buffering capability of the Bluetooth modules, no data loss was detected for the use cases described here.

The system's tree topology, with point-to-point data exchange between Bluetooth master–slave pairs, takes advantage of Bluetooth scatternet behavior, but avoids overhead imposed by *ad hoc* network functionality, such as dynamic routing [58], [59], subsequently improving data transmission efficiency. Ignoring Bluetooth inquiry and connection commands, each data packet consists of 260 B of data, encapsulated within an MIB packet (47 B of overhead), which are further encapsulated in a Bluetooth packet (6 B overhead). The overall data exchange efficiency of the entire system is 83% (user data bytes$\div$overall bytes$\times$100%.

V. DISCUSSION

This prototype system demonstrates that merging the MIB upper layer specifications and the Bluetooth stack is feasible. The MIB standards define information representation formats and specify system-level association, system configuration, and data exchange. Bluetooth provides the device lower layers and offers reliable connectivity, data transmission, and link management. The Bluetooth Host Control Interface mode provides the operations for constructing an *ad hoc* local area network (a.k.a. personal scatternet), so the upper application layers do not have to worry about lower layer flow control. This significantly improves system robustness and shortens development time.

For physiological measurements that require relatively low bandwidth, the Bluetooth transmission rate is adequate. However, for higher bandwidth signals, such as real-time waveforms or images, the current Bluetooth transmission rate (723 kb/s maximum forward data rate in air using DH5 asymmetric transmission) may become inadequate, because overhead and retransmissions will reduce the effective transfer rate, especially when many DLs and BSs coexist in an environment. Additionally, Bluetooth's baseband transceiver applies a time-division duplex scheme, where transmission and reception share a limited number of available time slots. Subsequently, the maximum packet size is limited by this scheme; in the DH5 mode, the largest packet size is 339 B. This is not ideal for a store-and-forward system, where large amounts of data may await uploading. In other words, as with any mobile wireless application, the approach presented here must be implemented with care in a multipatient environment where bandwidth-hungry sensors reside.

The MIB standards address information representation/exchange and device interaction, including the elements necessary to simplify medical device connection and setup. However, the standards were originally designed for bedside environments, making their application to mobile devices awkward. The MIB device architecture 1) is more static, 2) assumes the presence of resources normally available on desktop devices, and 3) demonstrates a reliance on cable connections. When these standards are applied at the resource-limited, embedded level, significant simplification work needs to be done to minimize computation and memory requirements. This means merging the layered functionality, simplifying interactions between layers, and combining services grouped in the standards.

In this effort, the largest deviation from MIB conformance resulted from the application of a wireless telemetry mechanism. Bluetooth, like other wireless data standards, imposes limits on the connection establishment protocol, PDU length, PDU format, and transmit rate. The MIB standards must therefore be modified to interface with off-the-shelf, wireless communication technology.

As a result of this work, the authors propose the following to the MIB technical committee regarding wireless MIB implementation in a home environment.

- Incorporate segmentation and reassembly into the Session layer, supplementing the current concatenation feature. This would support the use of wireless data packets, which are typically short.
- Define a more efficient device-synchronization approach that addresses issues associated with wearable/mobile devices, such as latencies inherent in wireless communication. Also, MIB defines a "relative time" data type: the number of clock ticks in increments of 1/8 s that occur after a reference. It would improve interoperability to define an event as an absolute time reference.
- Include nonmedical measurements, such as ambient temperature, in the nomenclature. Although the standards allow custom object definitions, it would improve device interoperability to standardize the nonmedical measurements most often used in a home environment.

VI. Conclusion

This paper outlines an approach for designing plug-and-play, point-of-care devices for home use, and presents a solution based upon existing standards: Bluetooth and IEEE 1073 (MIB), which implement both lower layer connectivity and upper layer interoperability, respectively. In this three-level system (BS↔DL↔SU), wearable devices are implemented as microcontroller-based, embedded systems that interact wirelessly with one another. To this end, the MIB standards were simplified and scaled down to the embedded level. Although these embedded components are limited by memory and processing speed, this demonstration shows that it is feasible to implement MIB-based, wearable devices and achieve the desired plug-and-play features of ease of use, reconfigurability, and scalability in a wireless BAN.

Additional efforts are underway to develop a capability based on Health Level 7 to remotely store patient data to an SQL database via the Internet [60]. This will promote data access by care providers and facilitate the use of remote algorithms for state-of-health assessment. The current system must also be updated to incorporate elements of security: 1) Bluetooth encryption between devices on the BAN; 2) mechanisms for authenticating the identity of the wearer prior to storing their data in a remote database; and 3) features to ensure that, e.g., a device on one person does not upload data to a DL worn by another person.

Finally, the lessons learned from this effort must be incorporated into a proposal to the Medical Device Communication Industry Group that summarizes the updates that must be made to the MIB standards if it is to be a viable candidate for wearable point-of-care systems.

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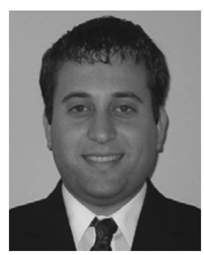

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