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Bluetooth Roaming for Sensor Network System in Clinical Environment

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Abstract

A sensor network is key infrastructure for advancing a hospital information system (HIS). The authors proposed a method to provide roaming functionality for Bluetooth to realize a Bluetooth-based sensor network, which is suitable to connect clinical devices. The proposed method makes the average response time of a Bluetooth connection less than one second by making the master device repeat the inquiry process endlessly and modifies parameters of the inquiry process. The authors applied the developed sensor network for daily clinical activities in an university hospital, and confirmed the stabilitya and effectiveness of the sensor network. As Bluetooth becomes a quite common wireless interface for medical devices, the proposed protocol that realizes Bluetooth-based sensor network enables HIS to equip various clinical devices and, consequently, lets information and communication technologies advance clinical services.

Keywords:

Sensor Network; Bluetooth; Roaming; Hospital Information System; Clinical Application;

Introduction

A sensor network is key infrastructure for advancing a hospital information system (HIS). A sensor network enables one to plug various devices including vital sensors into a HIS and lets the devices send obtained data directly to connecting HISs. Consequently, the sensor network frees clinical staff from posting vital data into a HIS and frees patients from clinical incidents caused by misposting of the data.

The sensor network enables us to divide complicated medical equipment, such as the echogram, into functional units and embed the equipment into a gigantic computer system, which is called hospital [1]. Embedded medical equipment with tiny sensing units, such as wireless ultrsound probes, frees clinical staff from carrying heavy medical equipment or patients to move to rooms with medical equipment, and enables the clinical staff to perform measurements anywhere. As a matter of course, obtained data can be directly stored to a HIS, and the data may enable a HIS to provide certain clinical diagnostic support in proper moment. Thus, embedding medical devices into a HIS can be a silver bullet to increase clinical productivity and safety by maximizing the benefit of information and communication technologies [2].

A sensor network can be realized by any wireless communication technology, such as WiFi, Zigbee, and Bluetooth. A recent increase of social consciousness of health promotes vital sign sensors to equip connectivity with mobile information terminals, such as smartphones. The most common standard to mediate communications among personal health devices is Continua Health Alliance [3], which defines the standard connection protocol via Bluetooth. Recently, the existence of the Continua promotes clinical sensors to equip Bluetooth. Thus, once Bluetooth equips roaming functionality for enabling sensors to move around and real time location functionality to locate those moving sensors, it can be a feasible technology for emerging clinical sensor network environment.

On the other hand, the Bluetooth protocol, which is originally designed as “wireless serial bus”, is not suitable for roaming. The conventional Bluetooth protocol requires a time-consuming “pairing” process to connect a host computational device with a client terminals such as sensors. In this paper, the authors propose a method to provide roaming functionality for Bluetooth, implement the proposed method as a commercial Bluetooth sensor network system, and evaluated the developed system during daily clinical tasks at the Kyoto University Hospital.

Methods and Materials

Figure 1 shows the state transition diagram of Bluetooth. A Bluetooth module goes into “Standby” phase when it is switched on. When a CPU sends an “Inquiry” command to the Bluetooth module in standby phase, the module moves into the inquiry phase and starts to search nearby Bluetooth devices for a master communication device. Once a Bluetooth slave device such as a headset or a keyboard catches an inquiry packet from the master communication device, it responds with a Frequency Hop Synchronization (FHS) packet. After exchanging the inquiry and the FHS packet, both master and slave devices move into the “Page” phase and exchange communication parameters. Finally, both master and slave device move into “Connect” and “Transmit” phases to start data exchange.

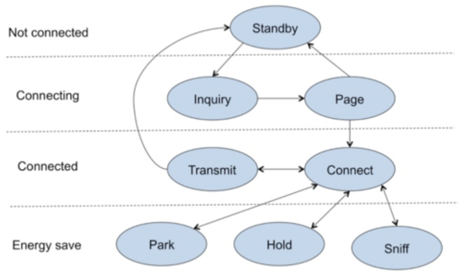


Figure 1 – The state transition table of Bluetooth

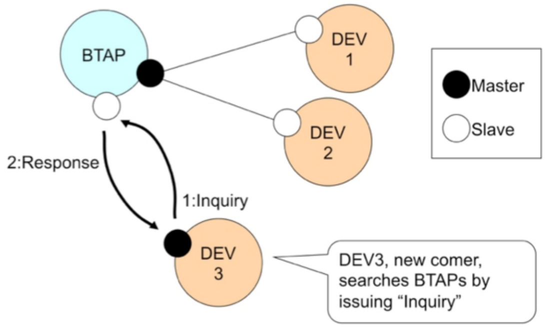
As a Bluetooth device moves into the page status immediately after discovery to wait for communication, a moving device, which is once coupled with a certain Bluetooth access point (BTAP), needs to wait for timeout to know that it is already out of reach of the BTAP. After that, the device needs to go through the inquiry process to find nearest BTAP. Moreover, the inquiry process is quite time consuming. The process requires approximately ten seconds. This limitation disables Bluetooth devices for smooth roaming under multiple BTAPs.

The authors made the master device suspend and restart the inquiry process in shorter periods by changing parameters, such as the master's inquiry interval and the slave's inquiry scan window size.When a master device suspends and restarts inquiry process every 640 milliseconds, the average response time to discover slaves becomes less than one second. As medical devices under operation in clinical environment will not move quicker than walking speed, the achieved response time, less than one second, is adequate to let devices move around.

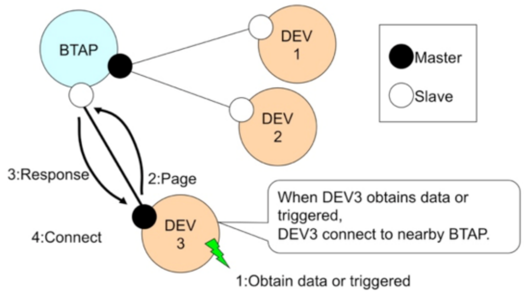
Once a device obtains certain data to send, the device should be paired with a BTAP within a reach. As the paring process initiated by the medical device, the proposed system makes the medical devices act as the master nodes during inquiry mode. On the other hand, to enable a BTAP to accept connections from multiple devices, the BTAP needs to act as the master node of the particular connection to keep slave channel open to accept incomming connection request.

Figure 2 shows the detailed protocol of the pairing process. In this diagram, a new comer (DEV3) tries to connect to a BTAP, which is connected with two devices (DEV1 and DEV2). In the beginning, DEV3 works as a master Bluetooth device to repeat the inquiry process as Figure 2(a) to keep finding nearest BTAP. When DEV3 obtains certain data to send, DEV3 immediately connects with the BTAP through the standard Bluetooth protocol as shown in Figure 2(b), then swaps their roles with the BTAP as shown in Figure 2(c). As a result, the BTAP keeps its slave channel open to accept an incoming device as shown in Figure 2(d).

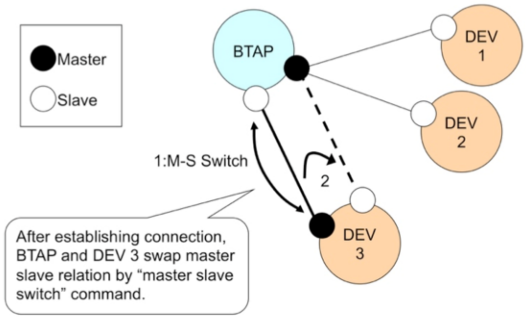
The BTAP keeps connection with DEV3 until DEV3 sends a termination code, an expected (pre-defined) data communication is finished, or the the BTAP detects timeout (Figure 2(e)). When DEV3 fails finishing communication, DEV3 goes back to inquiry process to find the nearest BTAP to restart the communication.



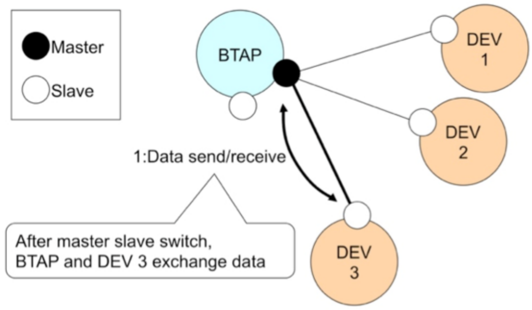
(a)



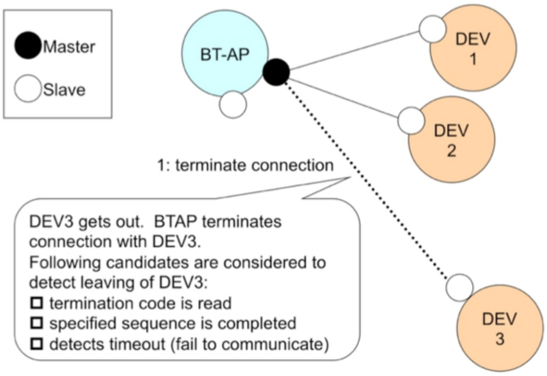
(b)



(c)



(d)



(e)

Figure 2 – The proposed pairing protocol (a) DEV3 keep finding BTAP by repeating inquiry phase. (b) DEV3 connects with BTAP. (c) DEV3 and BTAP swaps their role by master-slave switch command. (d) DEV3 exchanges data with BTSA. (e) DEV3 closes communication channel.

Results and Discussion

The authors developed and commercialized a Bluetooth-based sensor network system. The system provides a virtual serial port for a server to connect with Bluetooth devices over WiFi and Ethernet as shown in Figure 3. Figure 4(a) shows the developed BTAP (Takebishi Corp.).

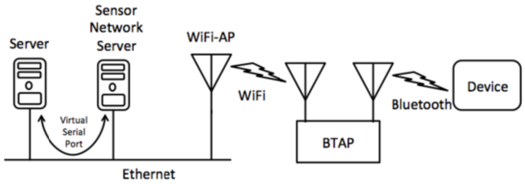


Figure 3 – Diagram of the developed Bluetooth-based sensor network system

(a) (b)

Figure 4 – The devices introduced to the hospital. (a) BTAP antenna (Takebishi Co.). (b) Barcode Reader (KoamTac Inc.).

Kyoto University Hospital [4] introduced the developed Bluetooth-based sensor network system with approximately 400 BTAP in 2011. The main target device was a Bluetooth-based barcode reader (KoamTac Inc. KDC 300, Figure 4(b)) for auto-ID / barcode enabled medication administration (ABMA) system [5]. Kyoto University Hospital introduced 1500 barcode readers. Each nurse and resident has a barcode reader for performing approximately 2700 safety checkups for transfusions and injections per day. Since January 2011, when the system was put into operation, the hospital has not experienced any major issues caused by lost communication, including roaming trouble, to the moment that this paper was written (April 2015).

The authors investigated all the comunication errors of the ABMA system on a standard business day, Thursday, October 9th, 2014. 2260 checkups were performed on the ABMA, and 32 communication errors occurred.

Figure 5 shows the basic communication protocol of the ABMA system. As the connection should be always initiated by the barcode device, the atomic communication of the system always consists of four messages, that is, barcode data, ack from server, response from server, and ack from the reader. During this atomic communication, no barcode device can change communicating BTAP.

As the ABMA checkup process consists of two atomic communications as shown in Figure 5, eight packets are needed to be sent to fulfill safety checkup. If any single packet within an atomic communication is lost, the ABMA system asks the clinical staff to re-read the barcode again. Therefore, the error rate of the observed day was $32 \div ((2260 + 32) \times 8) \times 100 = 0.17\%$.

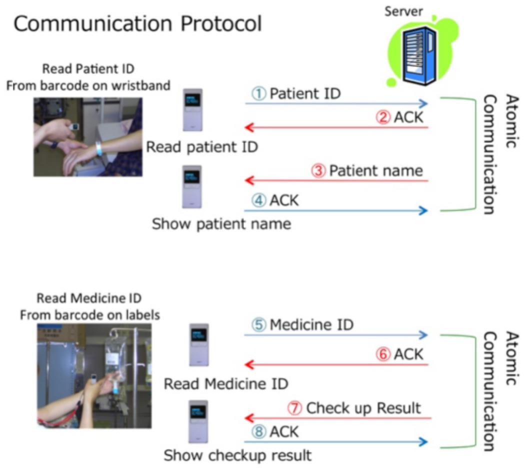


Figure 5 – Communication Protocol of the ABMA system

Additionally, packet can be lost during any connection between the device and the sensor network server. As shown in Figure 3, the communication is mediated by Ethernet and WiFi as well as Bluetooth. Thus, it is not the case that all observed error was caused by the roaming error of the developed system.

Thus, the developed roaming system worked quite well in the real clinical setup of Kyoto University Hospital, and provides clear efficiency for nurses to enable with their daily safety checkups with single tiny device. As a matter of fact, the average number of performed checkups per day increased from 1825 (January 2011) to 2260 (December 2014) after the introduction of the Bluetooth-based ABMA system. The number increased eight percent (from 1825 to 1973) in the first five months. This quite steady increase tells that the reliability of the ABMA system, supported by the realiability of the proposed Bluetooth roaming, earning the clinical staff trust. This fact clearly confirms the effectiveness of the proposed roaming mechanism.

As the proposed method realized by slight modification of the Bluetooth protocol, slight customization of firmware enables any Bluetooth-equipped devices, including the barcode reader introduced for Kyoto Univrsity Hospital, to connect to the developed sensor network.

The proposed protocol assumes that the connecting sensors send data intermittently. As the most of the vital sensing devices used in a standard hospital ward, such as blood pressure meter, body temperature meter, and weight meter, produce small size packets intermittently, just as the ABMA system implemented on the proposed sensor network that exchanges four short messages and four ACK packets. Therefore, the Bluetooth-based sensor network based on the proposed roaming mechanism may be able to accept most of such sensor devices.

On the other hand, in order to make the sensor network be enabled for continuous sensing devices, such as electrocardiogram (EKG) or oxygen saturation monitor (SpO2), certain compensation mechanism, such as buffering at the device side, should be considered.

Conclusion and Outlook

This paper proposed and implemented a method to provide roaming functionality for Bluetooth to realize Bluetooth-based sensor network for healthcare industries. The introduction of the developed Bluetooth-based sensor network system for daily activities in a university hospital with approximately 1000 admitted patients per day for five years clearly confirms the effectiveness and the availability of the proposed approach.

As the Bluetooth becomes a quite common wireless interface for medical devices, the Bluetooth-based sensor network may enable HISs to equip various medical and non-medical devices. Consequently, the sensor network expands capability of information communication technology to advance clinical services.

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