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An Ultra-low Power, Self-organizing Wireless Network and Its Applications to Non-invasive Biomedical Instrumentation

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Abstract This paper presents a newly developed short-range, ultra-low power wireless device called the "i-Bean", an ad hoc, self-organizing network protocol, and their application to ambulatory bioinstrumentation using a novel finger photoplethymo-graphic sensor called the "Ring Sensor". The i-Bean is made of commercial, off-the-shelf components, and functions as an integrated RF transceiver as well as data acquisition and processing device. The innovative design of the i-Bean circuitry results in extremely low power consumption for the device to run on a compact battery for exceptional long periods. A proprietary protocol allows multiple i-Beans to form ad hoc, self-organizing networks with optimal power efficiency. The Ring Sensor can measure arterial blood volume waveforms and blood oxygen saturation non-invasively and unobtrusively from the wearer's finger base. Combing the i-Bean and the Ring Sensor, a fully self-contained, wearable instrument has been developed ideal for on-line, long-term and continuous monitoring of vital signs.

1. Introduction

Fanned by the prevalence of mobile phones and cellular infrastructure in recent years, there have been dramatic advances in radio frequency (RF) technology and continued decreases in the cost of RF devices. More and more low-cost, high-performance RF devices and systems are finding their way in various applications that help improve productivity, increase user convenience, and enhance security and safety. Some prominent applications include wireless LANs, portable GPS receivers, Bluetooth, local area positioning, RFID, home automation, remote metering, and large-scale sensor networks, to name a few.

Increasingly RF technology has also been applied to ambulatory health monitoring in the home. A typical example is a home care device such as an electronic blood pressure meter or a glucose meter augmented with a low-power radio that transmits the measured data to a nearby computer for storage or further processing and transmission. Existing low-power, short-range RF devices such as Bluetooth are readily applicable to these home care units where power is relatively plentiful and RF transmission takes place sparsely. It has been long recognized in the health care industry that long-term, continuous monitoring is the key to preventive care for people with chronic conditions such as cardiovascular diseases. A number of research efforts have been dedicated to sensing devices for real-time, ambulatory health monitoring in the home. A radio link will be an indispensable element in a long-term monitoring system where measured data can be continuously unloaded from the sensing device and transmitted to a data collection center. To support long-term operation, the power consumption of the radio link must be minimized so that device users only need to carry a compact, lightweight battery such as the coin size batteries. For an RF device to run for a reasonable period of time on a 3VDC coin size battery, typically with 200mAh capacity, the average power consumption rate should be on the order of one milli-ampere (mA). Apparently the low-power devices like Bluetooth, which consumes 20 – 30 milli-ampere (mA) on average, cannot meet the requirement. Other emerging low-power RF devices, including those still being developed in research laboratories, could meet the stringent power constraint only with extremely low duty ratio, not practical for continuous monitoring purpose.

The free space loss model of RF signals shows that the radiated power is proportional to the square of desired transmission distance. A substantial amount of energy can be saved when antenna radiated power is reduced. Evidently it is more power efficient to emit low strength RF signals to travel a short distance and be relayed a number of times than transmitting high strength signals for a longer range. To relay low strength RF signals, repeaters must be installed at various places in the home to ensure complete radio coverage for continuous health monitoring. These repeaters should form a network using a protocol that supports multi-hop routing, so that data packets can be relayed from one repeater to another when the mobile RF terminal is far away from the base station. To minimize human intervention, the protocol should allow the repeater network to initialize itself in a highly ad hoc, self-organizing manner. For multi-user applications such as in the nursing homes where vital signs of multiple elderly residences should be monitored, the repeater network is required to communicate with all mobile RF terminals simultaneously. To manage data traffic among multiple terminals and repeaters, the network protocol must provide effective medium-access control as well as conflict resolution schemes.

As the population of aged people increases, close and continuous monitoring becomes more important. Real-time, continuous monitoring would allow not only for emergency detection but also for long-term assessment to establish the right dose and timing of medication. Especially, an ambulatory system that allows long-term monitoring of otherwise difficult and noncompliant patients such as demented elderly people is highly desirable. The ambulatory electrocardiogram (EKG) device (Holter [1]) has been used since 1960s. Although the Holter device provides reliable measurement of heartbeat, it is bulky, heavy, and cumbersome to wear for an extended period of time. In addition, its substantial power consumption forbids continuous operation using low capacity batteries. In recent years, lightweight devices based on photoplethymographic (PPG) sensing are emerging as a viable technology for continuous measurement of vital signs. However, accuracy of PPG measurement is highly susceptible to relative movement between the sensing element and the measured area. For ambulatory use, resistance of a PPG sensor to its user's motion artifact is the key design issue, and so far no reliable device is yet available for long-term use with a sufficient reliability.

This paper presents a novel wireless device, an intelligent network protocol and an innovative PPG sensor [2][3]. These technologies together address the unmet demand of long-term ambulatory health monitoring. In Section 2, the i-Bean, its network protocol and application models are discussed. The design and characteristics of the Ring Sensor are given in Section 3. Heart rate data measured by the Ring Sensor, an EKG instrument, and a fingertip PPG oximeter are compared and presented in Section 4. Conclusions are given in Section 5.

2. The i-Bean and the Self-organizing Network Protocol

The i-Bean is a self-contained, miniaturized computer with a built-in power source, flash memory, digital I/O interface, A/D and D/A converters, PWM generators, and a RF transceiver for bi-direction communication. The size of an I-Bean is no greater than three stacked US quarters. Figure 1 shows a picture of the i-Bean. Specifications of the i-Bean are given in Table 1. Main components of the i-Bean are an ultra-low power, short-range RF transceiver chip (RFC) and an 8-bit micro-controller unit (MCU). A novel design allows the RF and mixed signal circuits to be placed in close proximity. A device-level power saving algorithm is implemented on the MCU to achieve sub-milli-ampere current consumption for most operations. The principal idea behind this unique power saving algorithm is to minimize MCU idling time and the RFC duty ratio. Essentially the algorithm specifies the sleep mode as the *default* mode for MCU and RFC, which wake up only when there are specific tasks assigned to them. Consequently, in the *i-Bean*, MCU and RFC wake up and fall asleep much more frequently than the traditional computation and communication devices.

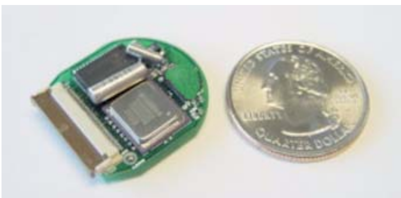

Figure 1: The i-Bean.

A base station with the architecture similar to that of the i-Bean can be connected directly to a host PC through the RS-232 serial interface. Communication between the i-Bean and the base station is bi-direction so that in addition to data acquisition and transfer from the i-Bean to the base station, the base station can transmit signals to the i-Bean to adjust certain operating parameters such as I/O channel selection and sampling rate, as well as to output data through i-Bean's output channels. A native protocol has been developed that supports not only the point-to-point communication between an i-Bean and the base station, but also a network of i-Beans in a self-organizing, ad hoc manner for multipoint-to-multipoint communication. To make up for the relatively short transmission range of the i-Bean (< 100ft), this protocol implements multi-hop routing through repeaters that relay data from i-Beans to the base station over an extended range.

Table 1: Specifications of the i-Bean.

Function/Feature	**Specifications**
Wireless Communication	Yes
Communication Distance	Up to 100 ft (30 m)
Frequency Band	Selectable from 300 to 900 MHz
Maximum Bandwidth	115kb/sec
Power Supply Type	Battery, 3VDC
Supply Current	< 1 mA
Network Mode	Point-to-point; point-to-multipoint; multipoint-to-multipoint
Flash Memory	8 KB
A/D Function	8 channels with 8 bits resolution
D/A Function	2 channels with 8 bits resolution
Digital I/O	8 channels
PWM Signal	2 channels
Sampling Frequency	50 Hz max.
Dimensions	0.93 in. X 1.00 in. X 0.20 in. 23.7 mm X 25.3 mm X 5.2 mm

Figure 2 shows a schematic of a typical network consisting of multiple i-Beans, repeaters and a central base station. The basic design of the repeater is similar to an i-Bean except for the larger memory space of the repeater to buffer data for routing. These repeaters can be randomly places at the installation site, and the embedded protocol can automatically coordinate these repeaters to form an ad hoc network and establish a highly effective routing map. This feature helps minimize human intervention for setting up and initializing the network, and is particularly useful for ambulatory applications in the home. Other prominent features of this protocol include:

Path-optimal routing
Data originated from any *i-Bean* will be transmitted to the base station via the shortest path that requires a minimal number of intermediate steps. The main advantages of this path-optimal routing are improved reliability of data transmission and reduced power consumption.

Dynamic re-routing
In the case where an intermediate repeater of a data route does not function properly, an alternative route will be automatically established to guarantee the reliability of data transmission.

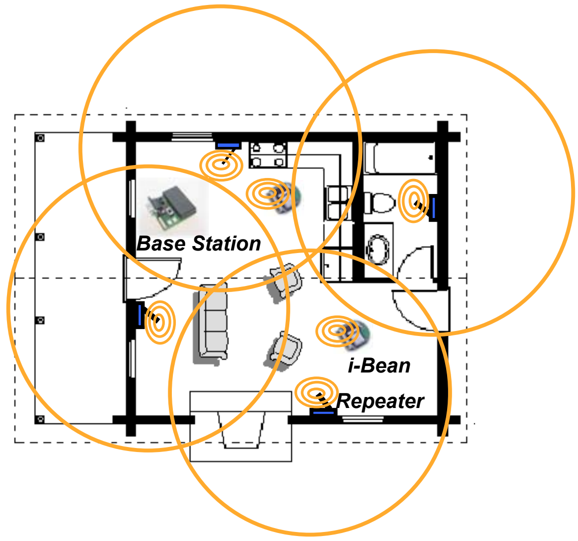

Figure 2: The i-Bean/repeater network.

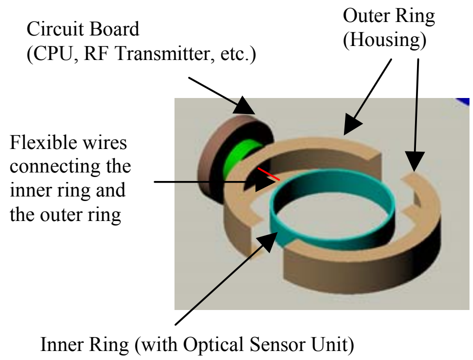

Figure 3: Construction of isolating ring.

3. The Ring Sensor

The finger ring is a unique form of wearable sensors and, probably, the only thing that the majority of people will accept to wear at all times. To monitor a patient twenty-four hours a day continually, a miniaturized sensor in a ring is a rational design choice. Other personal ornaments and portable instruments, such as earrings and wristwatches, are not continually worn in daily living. When taking a shower, for example, people remove wristwatches. Bathrooms, however, are one of the most dangerous places in the home. More than 10,000 people, mostly hypertensives and the elderly, die in bathrooms every year. Miniature ring sensors provide a promising approach to guarantee the monitoring of a patient at all times.

LEDs with two different wavelengths, red and near infrared, as well as a photodiode are imbedded in the ring facing inwardly. The red and infrared LEDs are alternately turned on and the output from the photodiode is amplified and switched to a sample-and-hold filtering circuit to generate a piecewise constant wave for each wavelength of light. This alternative and sample-and-hold sequence is repeated with a relatively high frequency to eliminate light interference even in a quickly changing background of room lights. The resultant waves are filtered and conditioned as photoplethysmograms. A 10-bit A/D converter samples each photoplethysmogram at the frequency of 30 Hz and the digital signals are transmitted by the i-Bean wireless networking technology. The whole process is scheduled and controlled by a single microprocessor on the ring. Transmitted photoplethysmograms are received and analyzed by a home computer. The technology of pulse oximetry is implemented on the computer for continuously monitoring the patient's pulses and blood oxygen saturation.

To alleviate the problem of motion artifact, a novel design was used in the ring sensor. The new design, called a "isolating ring configuration", is illustrated in Figure 3. The main idea of this design is to separate the sensor unit from the rest of the ring body that is much heavier than the optical sensor unit alone. The separation is achieved by having two rings that are mechanically decoupled to each other. The inner ring shown in the figure holds the sensor unit alone, while the outer ring contains the CPU, signal processing unit, battery, and RF transmitter. Only a thin, flexible cable connects the two rings. This decoupled design has the following advantages.

Alleviating the influence of external forces applied to the ring
Forces due to mechanical contacts are born by the outer ring, and are not directly transmitted to the sensor unit on the inner ring. As shown in Figure 2-(b), the load of the external force is bypassed to the finger bone and is supported by the two feet of the bridge-like outer ring.

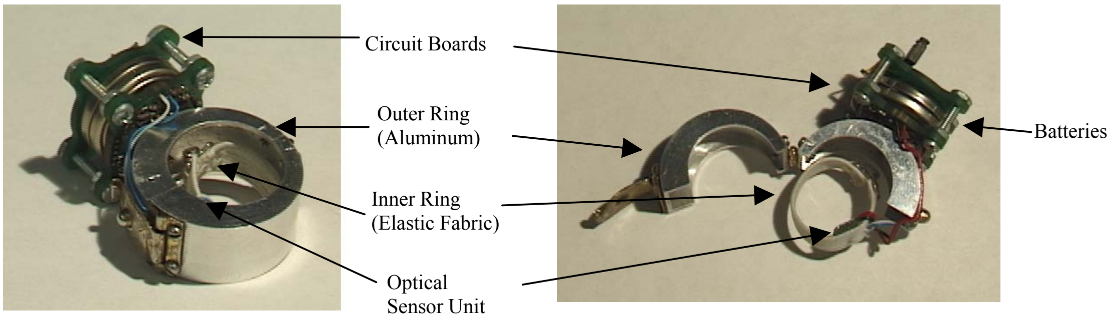

Figure 4: Isolating ring sensor designed for motion artifact minimization.

Thereby the force does not directly influence the actual sensor unit attached to the inner ring inside the outer ring.

Alleviating the effect of acceleration on the sensor
The inertia of the sensor unit is very small since it contains only a few LEDs and photodiodes. Due to the small inertia of the inner ring, the inertia force acting on the sensor unit is negligibly small. In consequence, the position of the optical sensor does not change significantly although the finger is accelerated.

Reducing the skin pressure
The outer ring doesn't have to be secured tightly, while the inner ring doesn't need a large pressure to secure the body, since it is light. Therefore, the possibility of necrosis caused by local ischemia and occlusion is lowered. This solves a critical problem for wearable sensors and long-term monitoring systems such as the ring sensor.

Reducing the influence of the ambient lighting
The outer ring shields the sensor unit and thereby reduces optical disturbances from the ambient lighting. The isolating ring structure provides the sensor unit with an optical shield. Figure 4 shows a picture of the isolating ring sensor prototype.

4. Heart Rate Monitoring Test

Figure 5 shows the beat-to-beat heart rate measured for the same subject when a light cardiac load was applied. The heart rate was determined by detecting the base point in each pulse and measuring the interval between adjacent base points. For benchmarking, the EKG and fingertip PPG data were simultaneously recorded, and the heart rate was extracted from each signal in the standard manner of beat-sampling technique [4]. The experiment was conducted for 60 seconds. As shown in the figure, the variation of heart rate has close correlation with that of the EKG and fingertip PPG.

5. Conclusions

A complete solution has been presented for long-term, on-line ambulatory health monitoring. The fully integrated i-Bean provides the RF link and embedded processing with minimal power consumption. An innovative protocol governs the repeater network to route data from multiple i-Beans anywhere at the installation site. The intelligent routing and message forwarding schemes ensure reliable data transmission and optimal power efficiency. The novel Ring Sensor with its effective motion-artifact resistance, compact form factor and low power consumption is an ideal device for long-term, continuous monitoring of vital signs. Benchmark results show that the performance of the Ring Sensor is comparable to those of the EKG and finger PPG devices.

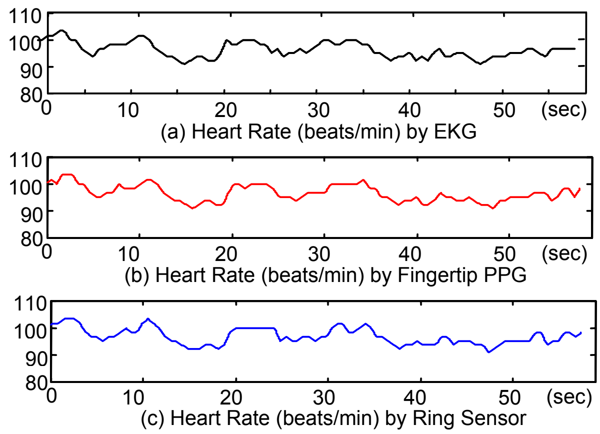

Figure 5: Heart rate monitored by EKG, Fingertip PPG device, and the Ring Sensor

References

[1] Holter, N. J., "New method for heart studies: continuous electrocardiography of active subjects over long periods is now practical", *Science*, vol. 134, pp 1214, 1961.

[2] Rhee, S., Yang, B-H and Asada, H., "Artifact-Resistant, Power-Efficient Design of Finger-Ring Plethysmographic Sensors" IEEE Transactions on Biomedical Engineering, 48 (7) (2001) pp 795-805

[3] Rhee, S., Yang, B-H. and Asada, H., "The Ring Sensor: a New Ambulatory Wearable Sensor for Twenty-Four Hour Patient Monitoring," Proc. of the 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Hong Kong, Oct, 1998

[4] J. D. Pruett, J. D. Bourland, and L. A. Gedded, "Measurement of Pulse-Wave Velocity using a Beat-Sampling Technique," Annals of Biomedical Engineering, Vol. 16, pp. 341-347, 1988