REVIEW

Wireless connectivity for health and sports monitoring: a review

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This is a review of health and sports monitoring research that uses or could benefit from wireless connectivity. New, enabling wireless connectivity standards are evaluated for their suitability, and an assessment of current exploitation of these technologies is summarised. An example of the application is given, highlighting the capabilities of a network of wireless sensors. Issues of timing and power consumption in a battery-powered system are addressed to highlight the benefits networking can provide, and a suggestion of how monitoring different biometric signals might allow one to gain additional information about an athlete or patient is made.

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Medicine and sports science can be considered as two linked but contrasting fields of research. Medicine is the science of diagnosing or monitoring the body for ailments that cause the patient to function in a manner that he or she or the doctor considers substandard, and to attempt to return the body to normality. Sports science strives to train and push the body to the extremes of its ability. The two disciplines are more closely linked in research that considers sports injury. Both therefore require a close study of the functions of the body, whether by means of vital signs such as heartbeat and breathing, or by the movement and function of muscles and joints. Often they combine individual variables to determine further information that no one variable can provide.

Such scrutiny of the body to determine its performance is often dependent on the environment in which the subject is being monitored. An athlete studied within laboratory conditions might perform quite differently from on the field. Likewise, monitoring a patient within the time constraints and artificial environment of the hospital might not give the same results as if the data were collected over a long period of time, during the patients daily routine. A further complication of multiple measurements or the collection of data over time might be the infrastructure of the equipment, primarily the size and the cabling constraints that might impede natural movement.

Technological advances have gone some way towards solving the issue of size—sensors, microprocessors and memory devices for processing and collecting the data are now miniature. Cabling, however, to allow multiple-site data collection, perhaps across the extremities of the body, or such that the patient remains completely unimpeded and mobile, remains a problem. Researchers and developers are beginning to look towards wireless technology to solve this.

GOING WIRELESS

Radio waves have been used as an information transmission medium for over a century (since Marconi in 1896), and yet it has only been in the last decade that wireless technology has begun to permeate everyday life to take on the tasks of wired equipment. Mobile phones, wireless internet and wireless data transfer between electronic devices have now become commonplace. Yet, in the fields of health and sports monitoring, where losing the constraints of wires might be most beneficial, the research that has been undertaken seems, from a wireless point of view, to be somewhat unimaginative.

The radio spectrum is a crowded medium, where there are strict regulations (governed by the Federal Communications Commission in North America and the European Telecommunications Standards Institute in Europe) over how and at what frequency you can transmit. There are segments of bandwidth within the radio spectrum that are allocated to licence-free use. These are called ISM frequency bands—industrial, scientific and medical—and, provided the user conforms to the rules for these frequency bands (eg, the maximum power that can be transmitted in the band and the power transmissions that are allowed to leak into adjacent bands), they are free to use.

There are several ISM bands in use in Europe and USA, predominantly for low-data-rate communications such as remote-controlled vehicle operation, garage door openers or keyless car-fobs, cordless telephone, and cable replacement. The emergence of the global ISM band at 2.45 GHz[1] (centre frequency) has brought about a number of radio standards that might be exploited for health and sports monitoring.

ENABLING WIRELESS TECHNOLOGIES

Many new wireless standards might at first glance provide the wireless platform for sensor networks. Three such standards occupying the 2.45 GHz ISM frequency are Bluetooth (http://www.bluetooth.org), Zigbee (http://www.zigbee.org) and Wireless Ethernet, and a fourth, occupying a higher band (3.1–10.6 GHz), is Ultra-Wideband (http://

Abbreviations: bps, bit(s) per second; GPRS, general packet radio service; ISM, industrial, scientific and medical; PDA, personal digital assistant

Glossary

Bluetooth: A short-range radio technology operating at 2.45 GHz

Data fusion: The integration of data collected from different sources by different methods to gain more information than the individual data can give—"sum of the whole is greater than the sum of the individual parts"

Data rate: Raw rate of date transmission in bits per second (this does not take into account the additional overhead data that needs to be added to transmitted information)

ETSI (European Telecommunications Standards Institute): An organisation dedicated to standardising telecommunications throughout Europe (European equivalent to FCC)

FCC (Federal Communications Commission): A US government agency that regulates interstate and international communications including wire, cable, radio, TV and satellite

GPRS (General Packet Radio Service): An enhancement to GSM mobile communications that supports data packets

Information rate: The rate of actual information transfer by radio (less than the raw data rate)

ISM (industrial, scientific and medical): Licence-free radio bands

Master (node): The controlling radio within a radio network

PDA (personal digital assistant): Palm PC

Pico-nets: A network of devices connected in an ad hoc fashion using radio technology (eg, Bluetooth). A pico-net is formed when at least two devices, such as a portable PC and a cellular phone, connect

RFID (radio frequency identification): An automatic identification method, relying on storing and remotely retrieving data stored on tags or transponders. An example is pet microchipping

Slave (node): A radio within a network that is controlled by the master radio, often with reduced functionality over the master node

Spread spectrum: A method that reduces radio interference to other radios and is more immune to interference from other radio sources; more radios can share the same frequency and security of data

UWB (ultra wide band): A short-range radio technology operating in the 3.1–10.6 GHz ISM band

Wireless Ethernet: Wireless Local Area Network (LAN) radio standard

Zigbee: A short-range radio technology operating at 2.45 GHz

www.uwbforum.org). Ultra-Wideband and Wireless Ethernet provide a higher data rate and range, and the resulting higher power requirements make them less suitable to low-power, short-range applications.

Bluetooth and Zigbee are often mistakenly thought to be very similar—both are low-power and short-range, operate in the 2.45 GHz band, and use spread spectrum (a transmission method; see Glossary). But subtle differences in the standards that govern these two technologies differentiate the markets for which they are most suitable. The Bluetooth mission statement describes it as the "provision of ad-hoc connections between devices used by humans", whereas Zigbee is described as "low power networked [as opposed to connected], and open standard".

A Bluetooth network is limited to one master node (module) and seven slave nodes, although many pico-nets can reside in one space and nodes can be members of more than one network. Zigbee supports networks of up to 65 000.[2] Power consumption is a large consideration for sensor networks. Bluetooth devices need to be constantly alert so that they can receive polls (interrogations) from the master node (the time the node can spend idle is limited). Zigbee has been designed with power consumption as a paramount consideration: consequently, the nodes can spend a large proportion of time asleep. Latency (the time from sleep-to-active), then becomes important: Bluetooth, 3 s; Zigbee, 15 ms.[3] The benefits of this are clear when you compare the power consumption of a Zigbee radio in different modes: active mode, <40 mA; sleep mode, 5 μA.

The data rate (how much information can be sent in a given time period) for Bluetooth is higher: 1 Mbps compared to Zigbee's 250 kbps. Thus, Bluetooth is more suited to voice, image and file transfer, and Zigbee to devices that communicate via small data packets. This highlights the differences in their complexity and in the resources they require—the Bluetooth protocol stack (the commands it uses to operate) is typically 250 kilobytes compared with Zigbee's 28 kilobytes.

Zigbee applications centre upon remote sensing with flexible and extendable networks, whereas Bluetooth concentrates upon short-range cable replacement and device-to-device connections. They "are different by design, and optimised for different applications.[3]

Such wireless connectivity would clearly support unobtrusive, wearable equipment and benefit non-invasive monitoring. This would allow the collection and use of data, possibly in real time, and also potentially the comparison or combination of multiple athletes' data. Yet the degree to which sports or health research groups have embraced this technology is varied.

Where telemetering (taking measurements remotely) is seen as simply a means of transferring data from sportsmen or patients to a remote data-logger, the most common method is a simple point-to-point (one transmitter, one receiver) frequency modulation transmission using off-the-shelf radio transmitter–receiver modules. Wang *et al*[4] of Huazhong University, China, describe a multi-parameter rowing measurement system where data from sensors measuring oar force, stroke rate, boat speed and heart rate are collected, digitised and transmitted via a single-frequency modulation radio connection to a receiver on the riverbank. Fong *et al*,[5] of the Chinese University of Hong Kong, developed a wireless motion-sensing system using accelerometers (acceleration sensors) to monitor human movement in Cartesian space. Acceleration data in three axes were measured at a single point in the human body and transmitted wirelessly within the laboratory so that body movement unimpeded by wires could be monitored in real time.

Smith and Loschner's[6–8] (NSW Institute of Sport, Sydney, Australia) multi-sensored system for collecting oarsman and boat data (boat velocity, pin and stretcher forces, and oar angle) from a rowing boat adopts a similar off-the-shelf device, although one specifically designed for the acquisition of large data sets such as theirs. They use the "PocketLAB"—a personal digital assistant (PDA)-style lab control and data acquisition system—to transfer data from the boat to a laptop on the shore for some real-time processing.

A research group at Lulea, Sweden, focus their attention on the application of enriched media experience. Their work extends the principle of using radio frequency identification (a miniature transmitter which transmits its identification upon interrogation) to indicate when an athlete passes a particular point on a course (termed context awareness). They then wirelessly transmit the physiological and positional data of athletes such that spectators can gain further information on a particular athlete and follow their progress via the internet or television onscreen data. Two of their projects (presented respectively by Konberg and Hallberg) make use of the Bluetooth to some degree to achieve this goal. Konberg and

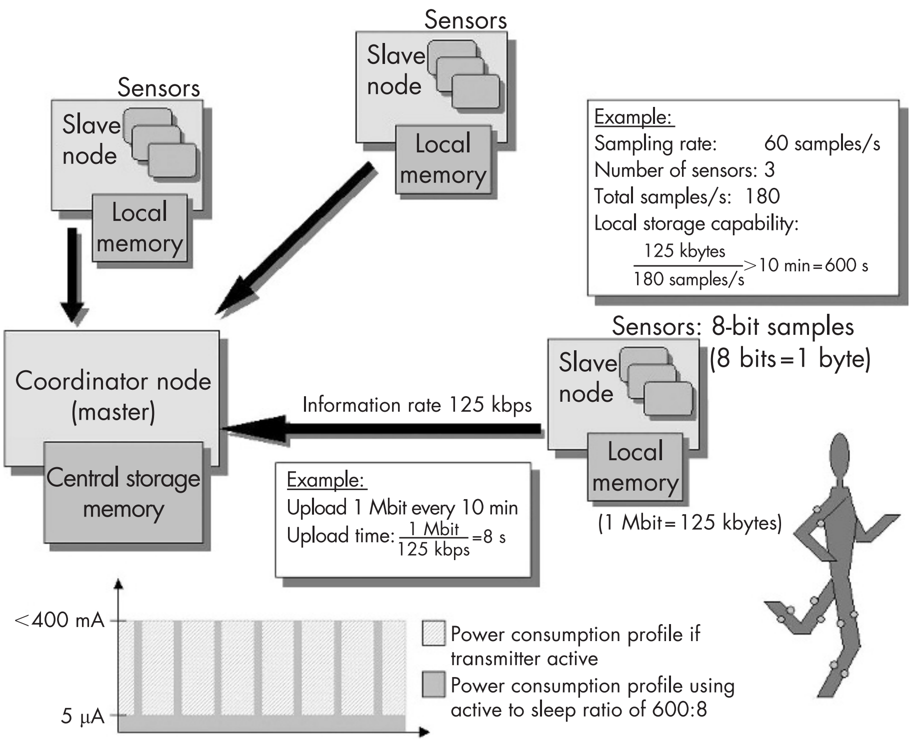

Figure 1 An example of the application: networking sports measurements.

colleagues[9] have developed a system for the monitoring of hockey players, transmitting heart rate and breathing data to the rink side. Although the idea was clearly for multi-player involvement and transmission via Bluetooth, the system was finally tested on one player, with a data modem fulfilling the task of data transmission.

The system of Hallberg *et al*[10] is more ambitious. The system was developed to monitor the heart rate and position/altitude information of cross-country skiers, and uses Bluetooth to transmit data to a Bluetooth/general packet radio service (GPRS—a mobile phone enhancement)-enabled mobile phone carried by the athlete. Data transmitted by GPRS can then be uploaded to a dynamic website so that the progress of the skiers can be followed via the internet. The networking capabilities of Bluetooth are considered in a limited fashion, and sensors upon the body are connected to sensor nodes that are Bluetooth enabled. In this way it was envisaged that more than one sensor node could connect to the mobile phone wirelessly. In reality, only one sensor node seems to have been connected in this way, as Bluetooth communication to a mobile phone is restricted to one device. Results from their experimentation were intermittent but encouraging.

The literature on ubiquitous healthcare monitoring or telemedicine is extensive,[11–30] but in most cases imagination seems limited to a single Bluetooth connection[19–30] between a sensor or a clutch of sensors and a base station. This base station often takes the form of a mobile phone or PDA with GPRS capability to send the data to a remote location or internet site. A typical example is that of Rasid and Woodward[20] at Loughborough University, Leicestershire, UK. Their system monitors ECG signals (to measure rate, rhythm and heart muscle blood flow), blood pressure, body temperature and saturation of peripheral oxygen (SpO_2). These signals are digitised in a Bluetooth-enabled processing unit worn on the patient's body, and from here transmitted via Bluetooth to a Bluetooth-capable mobile phone. The data can then be sent via a GPRS mobile network to the hospital.

A few research groups have extended this principle to encompass a small network of smart sensors.[11–17] Here, rather than all sensors being wired to a single Bluetooth-capable processing unit, each sensor, or collection of sensors, has its own Bluetooth radio. The Bluetooth radio standard allows up to eight Bluetooth devices to form an ad hoc network. An example of this is the wearable medical sensor network developed by Park and Kang[17] at the Electronics and Telecommunications Research Institute, Taejon, Korea. Here, there can be multiple (up to seven) sensor communication modules to which one or more sensors can be wired. These are slave Bluetooth nodes that transmit their data to a master central monitoring unit, also worn on the body, thus forming a wireless pico-net. Data can be transmitted from the central monitoring unit to a remote location via a modem or Bluetooth.

A similar methodology has been proposed by Choi *et al*,[11] from the Seoul National University, Seoul, Korea, but there the Bluetooth pico-net is installed within a bedroom. Jovanov *et al*[18] from the University of Alabama, Tuscaloosa, Alabama, USA, although not the first to note the advantages that Zigbee might have to offer for unobtrusive health monitoring, have also developed a prototype for ambulatory monitoring of user activity. Their system uses three wireless Zigbee sensor nodes connected to a PDA on the patient's body, which can then transmit the data to a remote location via the internet. Jovanov points out the importance of extending battery life for such applications, and also the benefits of improving the reliability of data through the fusion of information from different types of sensors. Jovanov's research on a Wireless Body Area Network of Intelligent Sensors[31] highlights the possibilities of monitoring data sampled synchronously from a group of subjects—specifically, monitoring heart-rate variability—to study the correlation with stress level. Jovanov's colleagues Raskovic *et al*[32] also pointed out the importance of wireless networks in corrective intervention in patients (eg, applying appropriate stimuli to a malfunctioning organ). In his review, he subdivided usage into four categories: recording, processing, correction and replacement.

Although these few research groups have begun to explore the possibilities of a personal wireless network or wireless body area network (as opposed to a single point-to-point connection), few seem to truly see the possibilities that Bluetooth, Zigbee or other similar networking radio systems afford. It should be possible, using wireless pico-nets, to be able to gather a vast and diverse data set of biomechanical information on health that can be combined to extrapolate further information not directly accessible from any single measurement type. This type of data fusion is hinted at by Ouchi *et al*, Toshiba, Tokyo, Japan,[16] who have developed a wearable heathcare support system. This, although employing only a single Bluetooth connection from the sensor module to a PDA, does show data fusion potential in their development of an algorithm to detect the beginning of a meal from the patient's pulse rate and galvanic skin reflex.

EXPLORING THE POSSIBILITIES OF WIRELESSNESS

The concept of replacing a network of wires with a wireless network is just the first step towards taking full advantage of what these new wireless standards can offer. Beyond just breaking the connection with data measurement (the sensor) and data storage, it allows measurements across the body or between other remote locations to be synchronously taken and stored.

In order to do this, the network of wireless measurement nodes must be coordinated and controlled by one central node. This master node will allow other slave nodes to be added to the network, to keep track of these nodes and of what data they are measuring, and to synchronise the logging of data. This master node might also be the location of the data storage, and would thus ensure that data are collected across the network of wireless nodes and stored such that data synchronously collected from numerous locations can be stored sequentially against time and location stamps.

Time synchronisation between the wireless nodes has an impact beyond just the collection of synchronous data. It also has an effect on a vital part of any personal wireless network—battery size and longevity. With knowledge of the number of nodes in the network, if each node has a modest amount of local memory, it is possible for the wireless component of each node to sleep (enter a low-power mode) and to awake at scheduled intervals to listen to the commands from the master node or to upload data to the central storage.

For example, a network logging muscle electromyographic data, galvanic skin response and pulse rate might consist of 12 slave nodes, each logging data from three sensors. If each node had 1 megabit of local memory storage, each sample was 8 bits (1 byte), and samples were taken at 60 samples/s, each node could store in excess of 10 min of data in between uploads of data. This mathematical model could be scaled up or down according to the number of nodes in the network, the number, size and frequency of data samples, and the amount of local memory per node.

The information rate (rate of information transfer differs from the raw data rate) for a 2.4 GHz Zigbee radio is 128 kbps, which, for the above scenario, translates to a data upload time of 8 s. A Zigbee radio node that has an active current consumption of $<$40 mA and a current consumption in sleep node of 5 μA would thus have a sleep-to-active ratio of approximately 600:8 s, and could therefore extend its battery life by a factor of about 75 (precise savings would depend on the power drawn by other electronic circuitry on the slave nodes).

Such a system (fig 1, an example of the application: networking sports measurements), just one example of the possibilities that wireless networks afford, might allow the muscle work, heart rate and sweating profile of an athlete to be monitored over a specific exercise, thus allowing further insight into, perhaps, an athlete's fitness.

What is already known on this topic

- The ability to take multiple measurements over the human body or other apparatus would clearly be greatly improved without the need for connecting wires to collect the data and power the measurement equipment.
- It is generally understood that transmitting data by radio might allow such wireless measurement to take place, and that battery-powered measurement equipment would further reduce the requirement for wires.

What this study adds

- This study provides a survey of wireless measurement systems for health and sports monitoring and presents a useful introduction to the new wireless technologies that could be exploited to enhance the measurement process.
- Through example, this study suggests how Zigbee radio networks might allow wireless measurements while minimising power consumption such that battery-powered measurement could be used.

CONCLUSIONS

The broad range of research that health and sports monitoring encompasses would benefit enormously from this ability to collect data unobtrusively and without hindering movement or performance. These data could relate information about the functioning of the body and the relative movement, in addition to any other performance-related data that might be desirable. New wireless connectivity radio standards could facilitate this data collection, allowing data to be collected synchronously from multiple points across the body. This would enable data from different sensors to be compared at specific points in time, and also allow them to be combined, by data fusion, to allow further interpretation of the data. Bluetooth and Zigbee, both wireless connectivity standards that allow the creation of wireless networks of data collection nodes (and in particular the newer of the two, Zigbee, whose main target application is sensor networks), are as yet an unexploited potential. Utilisation of their full capabilities could allow many health- and sports-monitoring research areas to step into a new territory previously fenced off by wires.

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COMMENTARY 1

The authors present a survey of wireless monitoring systems for health and fitness monitoring applications. This is an emerging trend inspired by recent developments in wearable computing and sensor technologies, with an increasing number of new applications. A wireless body area network of intelligent sensors allows prolonged, unconstrained monitoring during practice or normal daily activities.

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COMMENTARY 2

The paper introduces readers to some of the technicalities associated with wireless technologies in medical and sports science applications. In reviewing relevant publications, the paper highlights the benefits to be gained from the use of wireless systems, while emphasising the apparent lack of exploitation of these new technologies in the two named fields. The review largely focuses on the collection and transmission of biological measurements, but does reference a small number of examples where the wearer's position and movements have been monitored in sporting contexts. The examples given include media applications which provide feedback to broadcasters and spectators, and a limited number of sports science support applications where, for example, rowing forces and kinematics have been monitored. Overall, the paper provides a good general introduction to the topic.

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