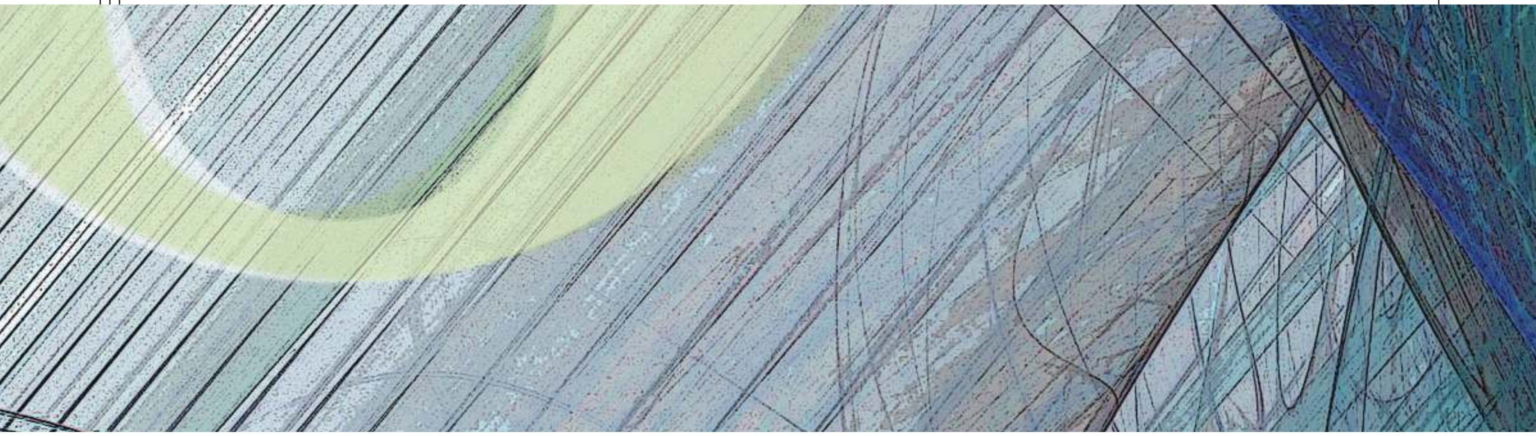
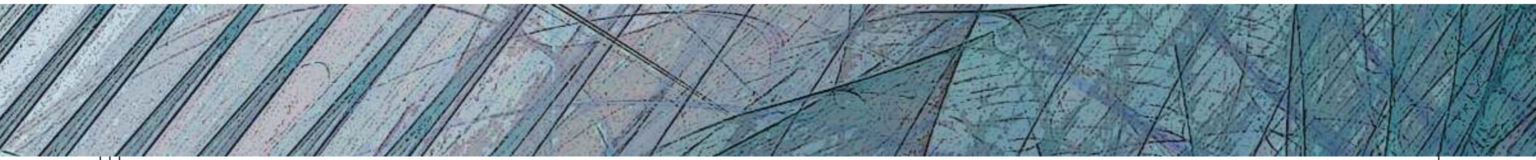


BODY AREA SENSOR NETWORKS: CHALLENGES AND OPPORTUNITIES



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Body area sensors can enable novel applications in and beyond healthcare, but research must address obstacles such as size, cost, compatibility, and perceived value before networks that use such sensors can become widespread.

Inroads into coordinated, intelligent computing are enabling sensor networks that monitor environments, systems, and complex interactions in a range of applications. Body area sensor networks (BASNs), for example, promise novel uses in healthcare, fitness, and entertainment. Each BASN consists of multiple interconnected nodes on, near, or within a human body, which together provide sensing, processing, and communication capabilities.

BASNs have tremendous potential to transform how people interact with and benefit from information technology, but their practical adoption must overcome formidable technical and social challenges, as the "Requirements for Widespread Adoption" sidebar describes. These challenges have far-reaching implications but offer many immediate opportunities for system design and implementation.

Although BASNs share many of these challenges and opportunities with general wireless sensor networks (WSNs)—and can therefore build off the body of knowledge associated with them—many BASN-specific research and design questions have emerged that require new lines of inquiry. For example, to achieve social acceptance, BASN nodes must be extremely noninvasive, and a BASN must have fewer and smaller nodes relative to a conventional WSN. Smaller nodes imply smaller batteries, creating strict tradeoffs between the energy consumed by processing, storage, and communication resources and the fidelity, throughput, and latency required by applications. Packaging and placement are also essential design considerations, since BASN nodes can be neither prominent nor uncomfortable.

As with any technology, economic concerns can affect BASN adoption. To amortize nonrecurring engineering costs, each BASN platform will require either significant volume in a single application or aggregate volume across

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several applications, creating design tradeoffs between application-specific optimizations and general-purpose programmability.

Finally, value to the user will ultimately determine the technology's success. BASNs must effectively transmit and transform sensed phenomena into valuable information and do so while meeting other system requirements, such as energy efficiency. A BASN's value therefore rests in large part on its ability to selectively process and deliver information at fidelity levels and rates appropriate to the data's destination, whether that is to a runner curious about her heart rate or a physician needing a patient's electrocardiogram. These disparate application requirements call for the ability to aggregate hierarchical information and integrate BASN systems into the existing information technology infrastructure.

Current work to address these challenges and realize these opportunities points to a critical need for collaboration between technologists and domain experts who can help define the specifications and requirements for BASN systems and applications. In applications targeting the aging population, for example, such collaboration could involve physicians, nurses, psychologists, and sociologists to ensure that a BASN provides valuable information while being usable by the elderly in a safe and socially acceptable manner. The need for such collaboration is only one of many requirements that research must satisfy to pave the way for practical, accessible BASN use.

APPLICATION AREAS

Because of demonstrated need and market demand, BASN research thus far has concentrated on healthcare applications, addressing the weaknesses of traditional patient data collection, such as imprecision (qualitative observation) and undersampling (infrequent assessment).

In contrast, BASNs can continuously capture quantitative data from a variety of sensors for longer periods. By addressing challenges such as the energy-fidelity tradeoff, BASNs will enable telehealth applications—medicine beyond the confines of hospitals and clinics[1]—and, because of their human-centricity, will facilitate highly personalized and individual care. As Figure 1 illustrates, BASNs integrated with higher-level infrastructure will likely excel in healthcare scenarios, serving the interests of multiple stakeholders.

In addition to delay-insensitive applications such as longitudinal assessment, BASNs that can offer real-time sensing, processing, and control will augment and preserve body functions and human life. BASN researchers are already working to improve deep brain stimulation, heart regulation, drug delivery, and prosthetic actuation. BASN technology will also help protect those exposed to potentially life-threatening environments, such as soldiers, first responders, and deep-sea and space explorers.

Finally, BASNs are well positioned to benefit from the intersection of two formerly disparate application areas. Physiological and biokinetic sensing applications

REQUIREMENTS FOR WIDESPREAD ADOPTION

Widespread BASN adoption and diffusion will depend on a host of factors that involve both consumers and manufacturers. User-oriented requirements include the following:

- ***Value.* Perceived value can depend on many factors, such as assessment ability, but overall, the BASN must improve its user's quality of life.**
- ***Safety.* Wearable and implanted sensors will need to be biocompatible and unobtrusive to prevent harm to the user. Safety-critical applications must have fault-tolerant operation.**
- ***Security.* Unauthorized access or manipulation of system function could have severe consequences. Security measures such as user authentication will prevent such consequences.**
- ***Privacy.* BASNs will be entrusted with potentially sensitive information about people. Protecting user privacy will require both technical and nontechnical solutions. BASN packaging will need to be inconspicuous to avoid drawing attention to medical conditions. Encryption will be necessary to protect sensitive data, and encryption mechanisms will need to be resource-aware.**
- ***Compatibility.* BASN nodes need to interoperate with other BASN nodes, existing inter-BASN networks, and even with electronic health record systems. This will require standardization of communication protocols and data storage formats.**
- ***Ease of use.* Wearable BASN nodes will need to be small, unobtrusive, ergonomic, easy to put on, few in number, and even stylish. On-body and off-body user interfaces will need intuitive controls and presentation of information.**

Beyond user concerns, BASN manufacturers will face imposing and expensive regulatory processes (FCC certification and FDA approval, for example) to get products to market. Once developed, BASN systems will likely involve a complex web of stakeholders (users, emergency services, caregivers, physicians, researchers, and so on). Each stakeholder will provide value to and derive value from BASN systems. Such dynamics create complex relationships that raise ownership and liability issues. Who will pay for BASN systems? Who will own BASN data? How will access to data and information be granted? Who is liable for damages involving BASN systems? These questions must be answered to protect all stakeholder interests and to promote BASN systems' widespread adoption and diffusion.

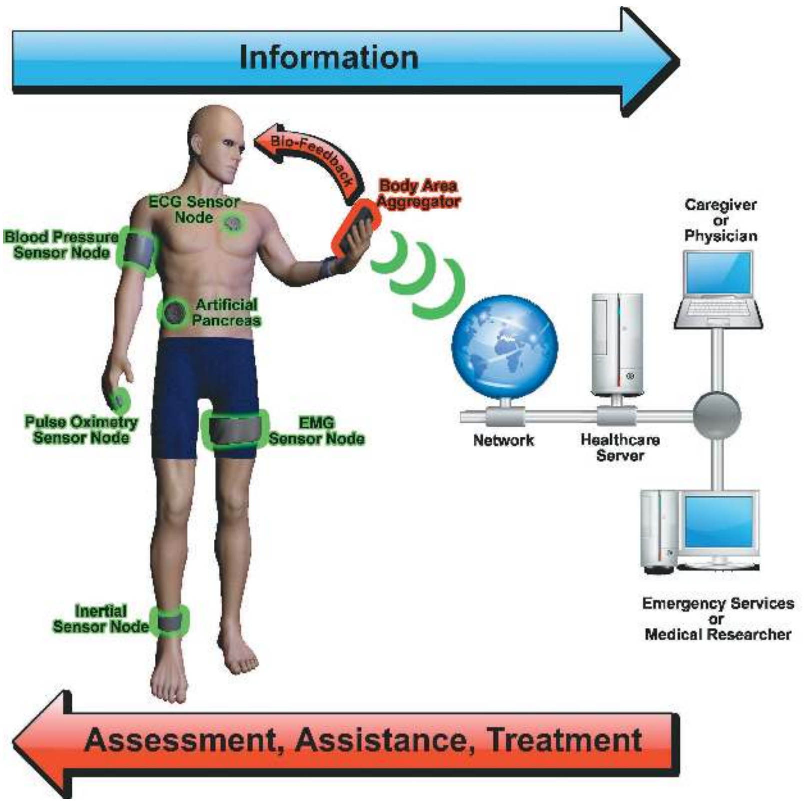

Figure 1. A body area sensor network and its environment. A BASN can interact with existing systems, such as networks in hospitals and retirement communities. Body sensors in BASN nodes provide data to the body aggregator, which is central to managing body events. Body aggregators perform a multitude of functions, including sensing, fusing data from sensors across the body, serving as a user interface, and bridging BASNs to higher-level infrastructures and thus to other stakeholders.

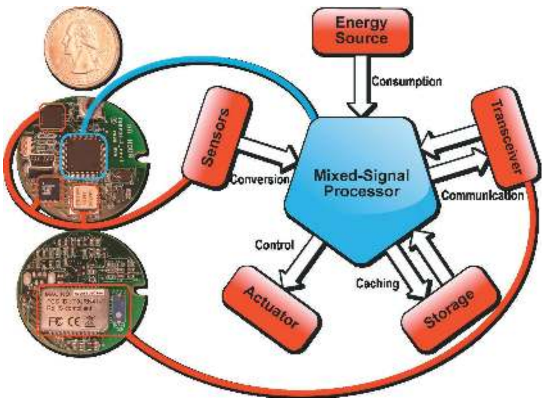

Figure 2. BASN node architecture. Although the architectural components are similar to those of a typical wireless sensor network node, a BASN node presents unique challenges and opportunities—from sensing to communication. The sensor node (left) is the TEMPO inertial sensor node developed at the University of Virginia.

are increasing as athletes and fitness enthusiasts seek to improve human performance, while gaming systems are pushing their envelope by integrating more sophisticated interfaces based on human movement. With the crossing of these markets, BASNs are well positioned to deliver the biofeedback and interactivity necessary for next-generation fitness and entertainment applications.

BODY AREA SENSING

As Figure 2 shows, BASN nodes create an interface to humans, typically encapsulating an energy source, one or more sensors, a mixed-signal processor, and a communication transceiver. Some nodes also support data storage or feedback control to body-based actuators, such as an insulin pump or robotic prosthetic. Although BASN and WSN nodes have similar functional architecture, differences in their operational characteristics—sensing, signal processing, communication, caching, feedback control, and energy harvesting—present unique challenges and opportunities for BASN nodes.

Sensors

Sensing is fundamental to all sensor networks, and its quality depends heavily on industry advances in signal conditioning, microelectromechanical systems (MEMS), and nanotechnology. Sensors fall into three categories. *Physiological* sensors measure ambulatory blood pressure, continuous glucose monitoring, core body temperature, blood oxygen, and signals related to respiratory inductive plethysmography, electrocardiography (ECG), electroencephalography (EEG), and electromyography (EMG). *Biokinetic* sensors measure acceleration and angular rate of rotation derived from human movement. *Ambient* sensors measure environmental phenomena, such as humidity, light, sound pressure level, and temperature. Although the number of sensors in the BASN in Figure 1 might seem unrealistic, BASN users are likely to tolerate and accept some degree of burden if they perceive enough value in doing so.

Sensors in typical WSNs are numerous, homogeneous, and generally insensitive to placement error. BASN sensors, in contrast, are few, heterogeneous, and require specific placement. Indeed, ineffective placement or unintended displacement from movement can significantly degrade the captured data's quality. Such requirements call for strategies that will minimize and detect placement error, such as better packaging combined with on-node signal classification.

Commercial sensors exhibit a wide range of power supply requirements, calibration parameters, output interfaces, and data rates. Figure 3 shows the power consumption and data rate across a sampling of commercial systems for continuous, ambulatory monitoring. Engineering BASN nodes to accommodate this breadth of sensing requirements could necessitate an application-specific approach that minimizes the design space, improves efficiency, and amortizes cost over a single application. Likewise, BASN nodes designed with a high degree of configurability could amortize cost over a much larger range of applications, including those unforeseen.

Signal processing

Signal processing is needed to extract valuable information from captured data that stems from transient events, such as falls, as well as from trends, such as the onset of fever. BASNs may need to concurrently capture, process, and forward information to different stakeholders. Time-critical information from both events and trends would go immediately to emergency services, for example, but information that is not sensitive to delays would go to the physician for review later on.

Figure 4 shows the power consumption of wireless transceivers and microprocessors in popular BASN and WSN platforms. It underlines two characteristics of existing embedded technology: Processing data at a given rate consumes less power on average than transmitting the data wirelessly, *and* reducing the data rate will reduce power consumption for both wireless transceivers and microprocessors. These characteristics create a tradeoff between processing and communication: On-node signal processing will consume power to extract information, but it will also reduce in-network data rate and power consumption.

Arbitrary data-rate reduction will lower the transmitted information's fidelity, and for lossy compression schemes, a rate-distortion analysis would need to define the limits of such a reduction. Low-power computational techniques such as dynamic voltage-frequency scaling or dynamic power management will create opportunities for dynamic adjustment of algorithmic complexity, and therefore trade off energy and fidelity based on an application's predefined or situational needs. Context-awareness and predictive models might better inform and guide processes that control data reduction.

Resource constraints challenge BASNs, including integer-only math, limited memory (< 20 Kbytes), and limited clock frequency (< 20 MHz). Therefore, BASN nodes must break complex signal-processing tasks into manageable segments to minimize algorithmic complexity while meeting real-time deadlines. Such efforts will necessitate operating systems that allow access to efficient hardware peripherals. In addition, work is needed to create feature-extraction algorithms and classification methods that are effective yet are not so computationally complex that they would be infeasible for resource-constrained hardware.

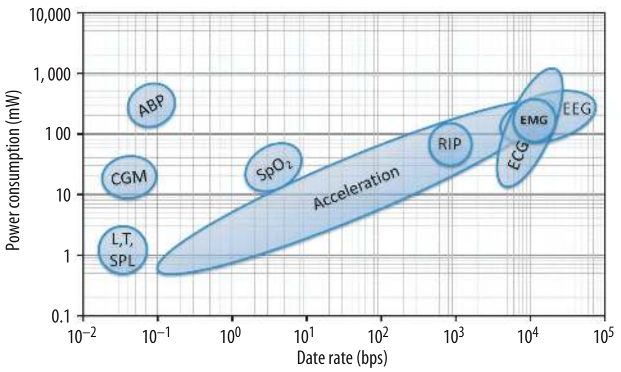

Figure 3. Average power consumption of continuous ambulatory monitoring applications. These differences suggest the need to support multiple applications in a narrow range of data rates (such as combining ECG, EEG, and EMG on a single node) or to support a single application across a wide range of data rates, such as acceleration. ABP: ambulatory blood pressure; CGM: continuous glucose monitoring; L, T, SPL: light, temperature, sound pressure level; SpO$_2$: pulse oximetry; RIP: respiratory inductive plethysmography; ECG: electrocardiography; EMG: electromyography; EEG: electroencephalography.

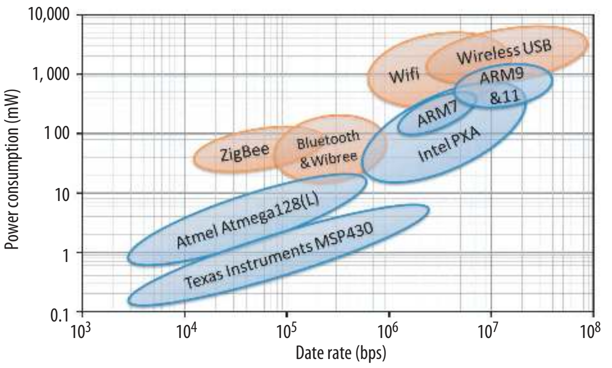

Figure 4. Average power consumption of wireless transceivers (orange) and microprocessors (blue) in typical BASN and WSN platforms. For a given data rate, wireless transceivers consume more power on average than processors. Reducing an application's data rate by extracting only the essential information will reduce power consumption.

Communication

Communication is essential to node coordination. BASNs are unique in that they attempt to restrict the communication radius to the body's periphery. Limiting transmission range reduces a node's power consumption, decreases interference among adjacent BASNs, and helps maintain privacy. WSNs typically communicate over radiative radiofrequency (RF) channels between 850 MHz and 2.4 GHz. Unlike WSNs, wireless BASNs are challenged by the dramatic attenuation of transmitted signals resulting from body shadowing—the body's line-of-sight absorption of RF energy, which, coupled with movement, causes significant and highly variable path loss.

> **The deployment and control of prosthetics or remote robotic assistive devices is a possible application of BASNs.**

Preserving quality of service (QoS) over traditional wireless links could require one of several approaches, including adaptive channel coding; transmission power scaling; multiple input, multiple output; novel transceiver architecture; and QoS-aware media access protocols. Ultrawideband communication could help mitigate aspects of this problem in the near future.[2]

Technologies such as smart textiles, magnetic induction,[3] and body-coupled communication[4] also show long-term promise. In *smart textiles*, wires are embedded in clothing, thereby reducing communication power overhead and simplifying networking schemes.[5] Cost, ease of cleaning, and manufacturer standardization could limit market uptake.

Magnetic induction uses magnetic near-field effects to communicate between two coils of wire. Near-field communication typically suffers less path loss than radiative communication, but coil dimensions complicate packaging. Despite this complication, implantable and swallowed sensors have exploited this communication technology.

Body-coupled communication uses the human body as a channel. BASN transceivers of this nature are either in contact with, or capacitively coupled to, the skin. Body-coupled communication is appealing because little radiated energy is detectable beyond the human body, channels are highly stable, and energy requirements are low. However, additional research will need to determine the safety of this approach.

Future BASNs might implement several types of transceivers to serve situational needs. For example, a sensor node could employ both lower data rate, lower power communication transceivers in parallel with higher data rate, and higher power transceivers for both longitudinal and critical communication needs. Transceiver diversity could also help mitigate body shadowing.

Storage

The microelectronics industry is exploring lower power nonvolatile memory such as MRAM and RRAM. Consequently, the availability of on-node storage might enhance BASN functionality. Because long-term data collection often needs no real-time aggregation, on-node storage is a reasonable solution for archiving data, thereby increasing battery life.

Longitudinal assessment is insensitive to delay metrics that challenge time-critical monitoring. Some applications might choose to cache data until body channel conditions are more favorable for transmission. Consequently, conditional caching could prolong battery life, decrease form factor, or decrease bit errors.

On-node storage could also be used to archive data for signal classification. By storing biokinetic gait patterns over time, for example, a BASN could learn to classify healthy gait from pathological gait. Such an archive could inform the signal-processing routines needed to detect longitudinal trends (recovery from surgery) and instantaneous events (falls).

Feedback control

BASNs open exciting opportunities for augmenting and assisting bodily functions. Medical devices such as deep-brain stimulators now run in an open-loop mode because no local feedback is available from the brain's central cortex to adjust the stimulator's excitation cycles. The accurate and reliable assessment of tremor through body area sensors could change that by empowering feedback tremor control.

The deployment and control of prosthetics or remote robotic assistive devices is another possible application. EMG signals from the eyelid or jaw might be used to control a device that assists or replaces a limb or to activate a robotic device that opens doors or controls simple household appliances. Other forms of feedback control include drug delivery and blood glucose regulation facilitated by implantable biochemical sensors.

Clearly, if BASNs are to control or help assess life-critical physiological events, they must be reliable. Unlike traditional WSNs, the failure of one BASN sensor could threaten life. Such applications will require fail-safe, fault-tolerant design principles.

Energy harvesting

Although the microelectronics industry has faithfully adhered to Moore's frenetic pace, advancements in commercial battery technology have been gradual. To remain a practical energy source for BASNs, battery technology must continue to increase energy density, and investments in increased energy density must have commensurate levels of investment in battery safety—particularly in light of recent battery recalls.

The high energy density of lithium-based batteries is helping power many portable consumer technologies. Such batteries work well for handheld electronics, but their capacity is limited in diminutive BASN enclosures. The need to replace or recharge batteries frequently makes BASN use less desirable. Supercapacitors and carbon-nanotube-based energy stores have great potential to improve battery capacity, but have not yet matured to commercial availability.

Energy harvesting—taking energy from ambient sources, such as sunlight or vibration—is an attractive solution to energy woes. Recharging batteries with harvested energy could not only extend battery life, but also simplify BASN use. Research challenges are formidable because of node placement variability and uncertainty about the user's exposure to ambient energy. These realities severely constrain opportunities.

Figure 5 shows the results of our investigation to estimate the average power that a BASN user can harvest per hour per day. For each of seven energy-harvesting sources,[6] we correlated the amount of power available per square centimeter with that source's availability during common human activities. We then compiled statistics from the US Department of Labor's 2007 "American Time Use Survey" (www.bls.gov/tus) on the percentage of Americans engaged in each activity at a given hour.

The figure shows an optimistic view of harvestable power, thus defining an upper bound for a system's power consumption from harvesting alone. The total power shown is available only if someone deploys all sources (at 1 cm^2 each) simultaneously and combines their power output. The data also illustrates a pronounced blackout period that renders these BASN nodes nearly powerless. Finally, the available harvestable power will differ substantially among individuals, which means it will be necessary to carefully match application profiles to activity levels in the target demographic.

Energy-harvesting sources vary widely in the energy available per area. For example, a solar panel in full outdoor sunlight provides up to 15 mW per square centimeter, but the same device generates only 10 μW in indoor lighting for the same area. Both placement and packaging would be affected by such variation.

Thus, although increasing battery life through harvesting would revolutionize BASNs, more research is needed to create highly efficient hybrid solutions that incorporate energy generation and storage.

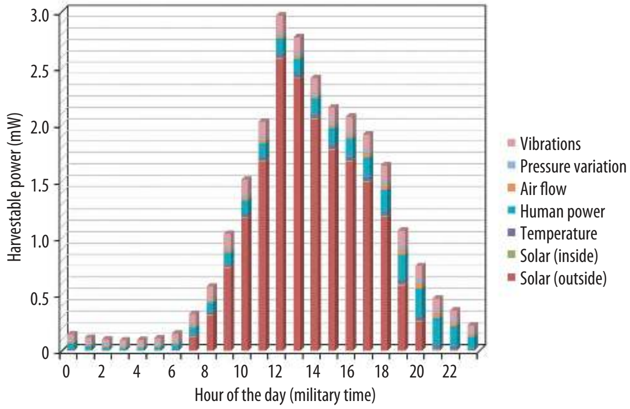

Figure 5. Results of correlating seven energy-harvesting sources with each source's availability over an average workday. Each segment represents the average amount of power that an individual could expect to harvest at any given time when all sources are being deployed. Nightly blackouts are a particular challenge and will require efficient energy storage mechanisms.

BODY AREA NETWORKING

Networking among devices in, on, and around the body poses unique challenges for resource allocation, sensor fusion, hierarchical cooperation, QoS, coexistence, and privacy. On the one hand, minimalistic networking techniques increase system runtime and reduce obtrusiveness; on the other, sacrificing QoS or privacy is unacceptable for life-critical or sensitive medical applications. BASNs introduce a wide range of application scenarios, yet it is not certain if a unified network solution is preferable over application-specific protocols and topologies.

Unlike conventional WSNs, BASNs are generally *smaller* (fewer nodes and less area covered) and have *fewer opportunities for redundancy*. Scalability can lead to inefficiencies when working with the two to 10 nodes typical of a BASN. Adding sensor and path redundancy to address node failure and network congestion might not be a viable strategy for a BASN seeking to minimize form factor and resource usage. Consequently, the focus must be on generating intelligent and cooperative QoS for the nodes.

On-body and in-body (implantable) networks exhibit *heterogeneity* because of placement constraints and sensor requirements. Wearability requirements can vary drastically across applications. Some call for multiple wired networks in a single garment; others call for multiple wirelessly networked devices securely attached at various body locations; and still others call for ultraminiature, biocompatible implanted devices with less frequent communication to the outside world.

BASNs also have a distinctly *hierarchical nature*. They capture large quantities of data continuously and naturalistically, which microprocessors must process to extract actionable information. Data processing must be hierarchical to exploit the *asymmetry of resources*, preserve system efficiency, and ensure that data is available when needed.

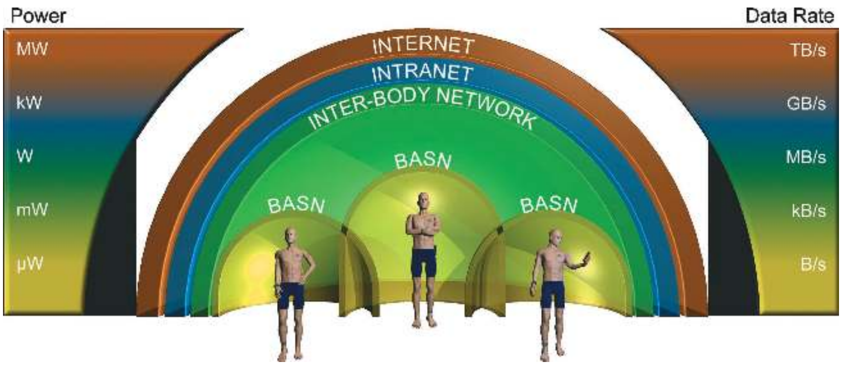

Figure 6. Hierarchy of networks and resources. Data processing starts with the individual BASN and progresses through communication with existing wireless technologies via the Internet. Because power consumption and data rate increase with each processing level, hardware and software will need to interoperate through multiple levels of infrastructure to share information.

Figure 6 shows the levels and their respective requirements for data processing, archiving, and management. During data fusion, systems can detect or react to notable occurrences from dynamic data, explicit queries, and so on. Specific reactions might include heightening the state of awareness, collecting data at a higher fidelity for closer inspection, forwarding events to higher levels, or even immediate response.

Aside from a BASN's inherent characteristics, designers must consider the *desired destination of sensed information*. Stand-alone BASNs route data for storage or for processing to another location in or on the body; other BASNs move data from the body through a gateway into other ambient networks. An example of integration with existing wireless technologies is an assisted-living facility, in which each resident's BASN wirelessly communicates to a back-end medical network. All the BASNs must maintain sufficient QoS by cooperating to mitigate network interference and transmit relevant information for further processing and presentation. BASNs should also encrypt information to ensure that only trusted stakeholders, such as physicians or caregivers, have access to it.

Hierarchical aggregation

Data processing at the sensor node reveals information specific to the sensor's locality. Information, however, might also come from relationships between data collected at multiple sensors over time. The body area aggregator has the important role of combining data from multiple sensors on the body.

The aggregator typically possesses a richer collection of resources and a greater energy capacity than the BASN nodes. In addition to its role as a data fusion center, the aggregator creates a bridge between the nodes and higher-level infrastructure. It can also offer user interfacing and can possess its own sensing capabilities. The convergence of wireless technologies, such as Bluetooth, cellular, and IEEE 802.11; interactive user interfaces such as touch screens; and highly capable embedded microprocessors, such as the ARM 11 and OMAP, make newer mobile phones and personal digital assistants attractive hosts for body area aggregation.

At the body aggregator, data processing must reveal relationships among a body's sensors. With progressively richer resources, more sophisticated and dedicated data-mining systems could uncover information related to small and large populations. Each successive hierarchical level must aggregate more data by supporting higher data rates, making more general inferences, and archiving more information. Consequently, hardware and software will need to interoperate through multiple levels of infrastructure to share information. Moreover, information gained at each level will provide feedback to and inform the refinement of classification schemes, feature-detection algorithms, and sensor coordination, placement, and design.

Topology

Star and star-mesh hybrid topologies show promise for meeting wearability, size, and data-fusion needs.[7] Both the star and star-mesh hybrid topologies exploit the resource asymmetry (aggregator versus node) and hierarchical nature of BASNs. In a star network, all peripheral nodes connect to the body aggregator, which allows for high data throughput and simplified routing. Having a central coordinator also means having a single point of failure, however. To address that weakness, a star-mesh hybrid topology extends the traditional star approach and creates mesh networking among central coordinators in multiple star networks. The failure of a single coordinator can trigger the reorganization of nodes and coordinators with minimal service interruption. Star-mesh hybrid topologies could also link aggregators and bridge networks from the body area to a wider area.

Coordination

Standards will help guide industry efforts by making it easier to fulfill the promise of compatible and interoperable networked technology. Fortunately, the IEEE 802.15.4 and the IEEE 802.15.6 working groups are leading the effort to address scalable, body-area network coordination.[8] ZigBee technology, such as the CC2420 (http://focus.ti.com/lit/ds/symlink/cc2420.pdf), employs the 802.15.4 Medium Access Control protocol to allocate guaranteed time slots to specific nodes. In this protocol, the coordinator prevents nodes from transmitting during other nodes' reserved slots. Collision avoidance and network coordination will be essential to maintaining QoS in both WSNs and BASNs.

Standardizing BASNs is not easy. Because of their hierarchical nature, they exhibit significant communication asymmetry, and all BASN nodes exist within range of each other, so they are likely to hear the entire network's transmissions. Another challenge is that BASN nodes will likely exhibit differences in transmitted data rates. Finally, BASNs that span application types, such as life-critical and non-life-critical, must coexist, and will require some scheme for prioritizing and encrypting messages. Addressing all these challenges is likely to require new approaches to media access and protocol design.

BASNs are enabling human-centric sensing for a variety of intriguing applications in healthcare, fitness, and entertainment, but such networks must demonstrate enough value for users to overcome inhibitions related to inconvenience, invasiveness, and general discomfort.

In his bestselling book, *Visions: How Science Will Revolutionize the 21st Century and Beyond* (Oxford University Press, 1999), futurist Michio Kaku described wearable technologies that will "silently monitor" heart rhythm, detect irregularities, and alert emergency personnel in the event of a heart attack. This vision, not far removed from current research efforts, illustrates the promise of BASNs in this important area.

But the promise of this technology should not be restricted to one area. Fitness and entertainment are taking new directions that are also well-suited to BASN architecture. The same architecture that captures body motion for medical assessment is equally adept at capturing body motion for a videogame. New sensors will only increase the breadth of potential applications and market opportunities and propel this technology into applications formerly depicted only in science fiction.

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