Wireless Sensors for Medical Applications: Current Status and Future Challenges

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Abstract

Continuous health monitoring using wireless body area networks of implantable and wearable medical devices is envisioned as a transformative approach to healthcare. Rapid advances in biomedical sensors, low-power electronics, and wireless communications have brought this vision to the verge of reality. However, key challenges still remain to be addressed. This paper surveys the current state-of-the-art in the area of wireless sensors for medical applications. It focuses on presenting the recent advancements in both wearable and implantable technologies. Furthermore, this paper addresses the challenges that exist in the various Open Systems Interconnection (OSI) layers and illustrates future research areas concerning the utilization of wireless sensors in healthcare applications.

Biography

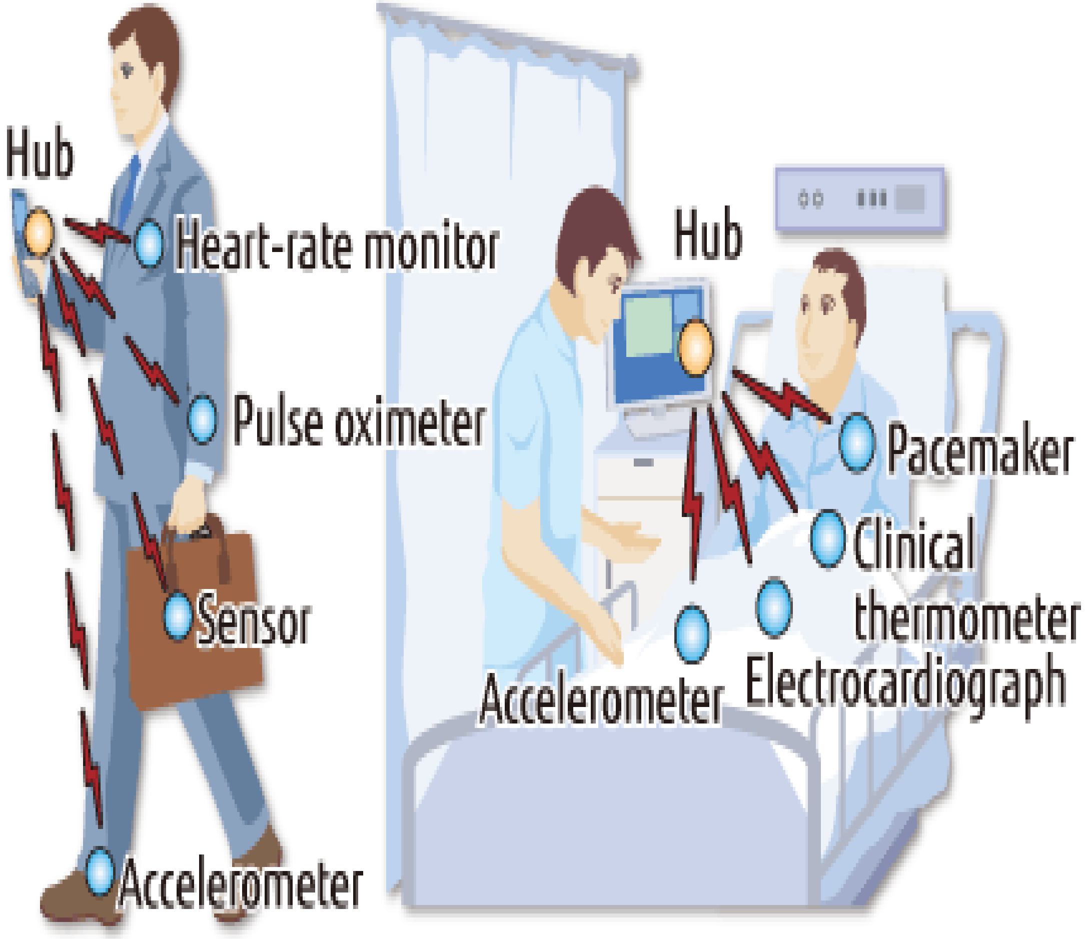
Raed Shubair (S'85, M'93, SM'01) is a Full Professor of Electrical Engineering. He is a Visiting Scientist at the Research Laboratory of Electronics (RLE), MIT Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology (MIT), USA. He is also Full Professor of Electrical Engineering at Khalifa University (formerly Etisalat University College), UAE which he joined in 1993 up 2017. Prof. Shubair received both his B.Sc. degree in Electrical Engineering (with Distinction and Class Honors) from Kuwait University, Kuwait in June 1989 followed by his Ph.D. degree in Electrical Engineering (with Distinction) from the University of Waterloo, Canada in February 1993. Prof. Shubair research interests include Antennas and Bioelectromagnetics, Terahertz Intrabody Communications, Wireless Nanosensor Networks, Internet of Nano Things, and Signal Processing for Wireless and Medical Applications. He has over 200 publications which include US patents, book chapters, papers in IEEE transactions and international journals, and papers in IEEE conference proceedings. He conducted several tutorials and workshops in international conferences, and delivered numerous invited talks at international academic institutions. Prof. Shubair received, several times since 1993, both the University Teaching Excellence Award and the University Distinguished Service Award. He is also recipient of several international research and professional awards. These include the 2005 Distinguished Service Award from the ACES Society in USA and the 2007 Distinguished Service Award from the Electromagnetics Academy in USA. Prof. Shubair supervised his students to receive several conference awards including the 2015 and 2016 IEEE IIT Conference Best Selected Papers Awards, the 2015 IEEE ICCSPA Conference Best Student Paper Award, and the 2016 IEEE BioSMART Conference Best Paper Award. He also supervised his students to receive several international awards and prestigious distinctions including the 2015 IEEE Student Travel Grants, the 2016 Vanier Canada Doctoral Research Grant Award, the 2016 IEEE Predoctoral Research Grant Award, the 2016 NSF Young Professionals Award, and the 2017 OSA Photonics Research Grant Award. Prof. Shubair has supervised and mentored his students to receive full scholarship postgraduate admissions and research internships at top universities in the USA (MIT, Harvard, Georgia Tech, SUNY), Canada (Waterloo, UBC, Carleton, Concordia), France (UPEM Paris University), as well as other universities in UK, Australia, and Switzerland. Prof. Shubair hosted invited talks by the Presidents and Distinguished Speakers of several IEEE Societies. He delivered many invited talks and seminars in top universities including MIT, Stanford University, Harvard University, University of California at Los Angles (UCLA), University of Waterloo, Carleton University, Ohio State University, University of Central Florida, Imperial College, and Queen Mary University of London. Prof. Shubair organized and chaired numerous technical special sessions in flagship conferences including recently EuCAP2017 and IEEE APS2017. Prof. Shubair is a standing member of the editorial boards of several international journals and serves regularly on the steering, organizing, and technical committees of IEEE flagship conferences in Antennas, Communications, and Signal Processing. He was appointed and serves as a member of the Organizing Committees of several flagship international conference including EuCAP2017, EuCAP2018, IEEE APS2017 and IEEE APS2018, IEEE WCNC2018, and ICASSP2018. He has served as the Technical Program Chair of IEEE MMS2016 Conference. Prof. Shubair holds several appointments in the international professional engineering community. He was appointed and serves currently as the Chair of IEEE APS Educational Initiatives Committee, the Outreach Chair for IEEE Antennas and Propagation Society, EuCAP Liaison for Middle East and North Africa. Prof. Shubair was selected to become a Member of the Board for the European School of Antennas (ESoA) since January 2017. He was also appointed as the Regional Director for the IEEE Signal Processing Society in the Middle East. Prof. Shubair is Guest Editor for the IEEE Journal of Electromagnetics, RF, and Microwaves in Medicine and Biology. Prof. Shubair is also the Co Editor-in-Chief of Journal of Electromagnetic Research and Application Technologies (FERMAT) founded by the world pioneer in the area and IEEE Life Fellow, Professor Raj Mittra. Based on his distinguished technical and professional contributions and accomplishments, Prof. Shubair is nominated for the 2017 IEEE Distinguished Educator Award.

Outline

- Requirements for Wireless Medical Sensors
- Wearable Wireless Body Area Networks
- Implantable Wireless Body Area Networks
- Challenges of Wireless Body Area Networks
- Future Directions

Requirements for Wireless Medical Sensors

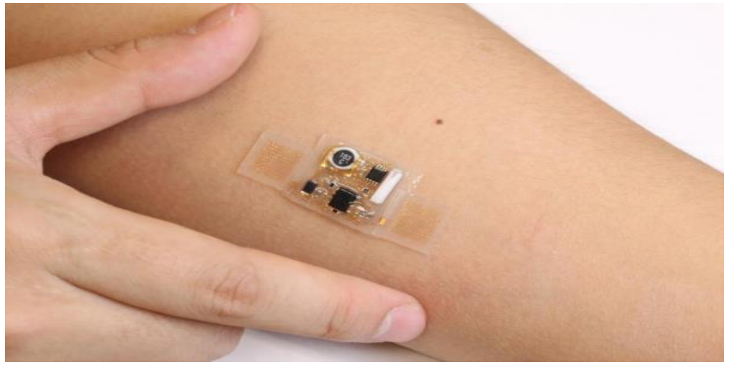
- To sense biological information from the human body and transmit it wirelessly over a short distance, wearable and implantable sensors are utilized.
- These sensors communicate the acquired information to a control device worn on the body or placed in an accessible location.
- The data assembled from the control devices are conveyed to remote destinations in a wireless body-area network for diagnostic and therapeutic purposes.

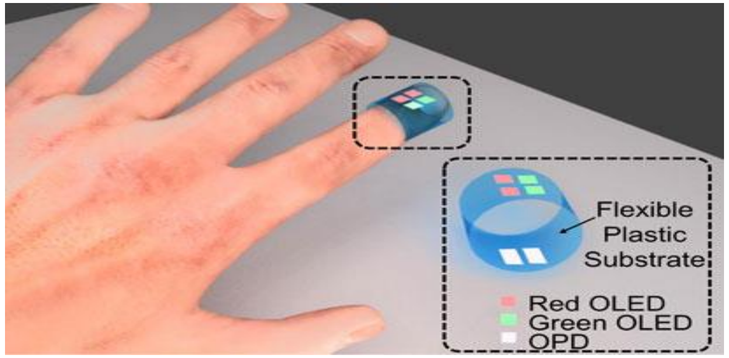


Requirements for Wireless Medical Sensors

Requirements

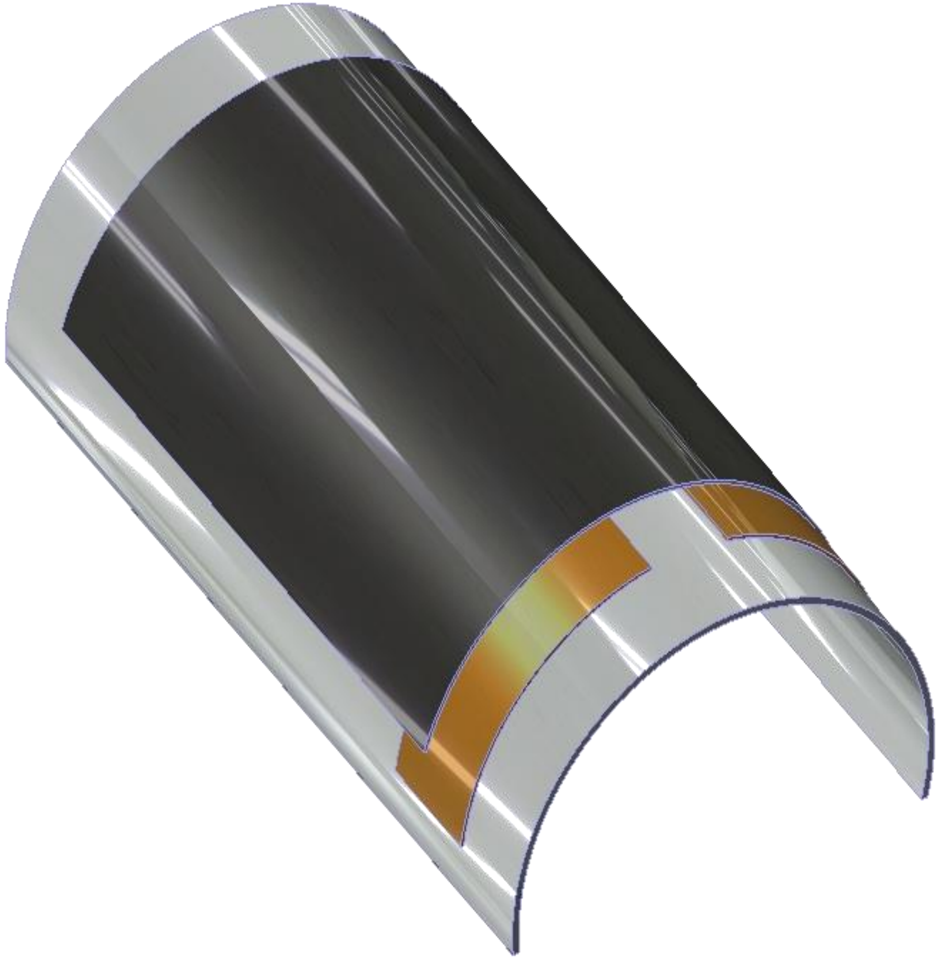
- Unobtrusiveness
- Security
- Interoperability
- Reliable Communication





Unobtrusiveness

- An essential requirement in the design of wireless medical sensors relates to their *light weight and miniature size*.
- These characteristics allow both non-invasive and unobtrusive continuous monitoring of health.
- The size and weight of a sensor rely on the size and weight of its battery, where a battery's capacity is directly proportional to its size.
- Recent technological advances in microelectronics, led to the development of small size, high energy batteries.
- Flexible and printed batteries both hold promise for wearable devices.



Flexible batteries offer a distinct advantage, including skin patches for transdermal drug delivery, patient temperature sensors, or RFID tracking.

Security

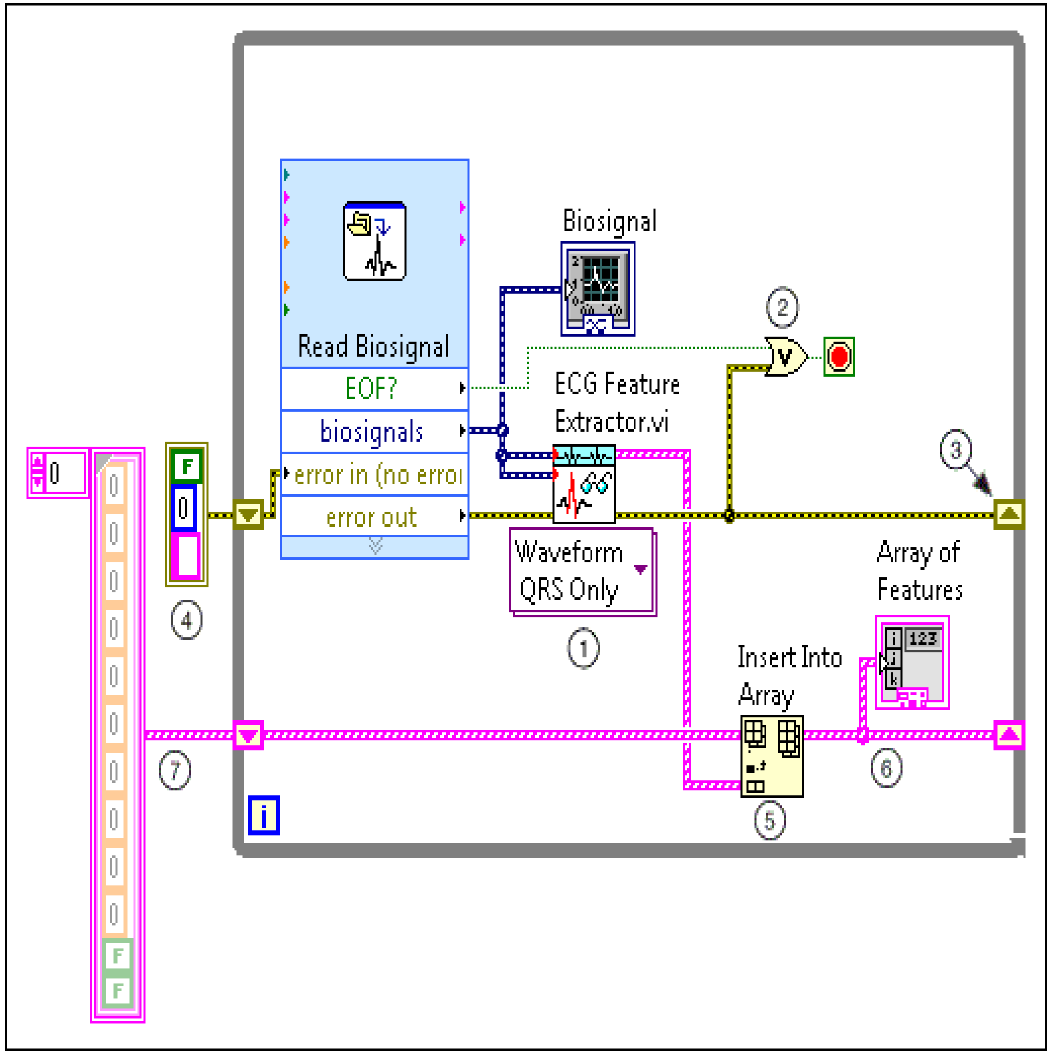
- One of the essential design fundamentals of a wireless body area network is the security of the entire system.
- Data integrity must be ensured where the sensors must fulfill the privacy requirements provided by the law.
- Basic software components must be identified and developed to accommodate secure and efficient wireless networks where data should be accessible by any authorized person in remote destinations.
- The coordination between the hardware components and the software program is fundamental to providing secure and reliable communication.

Interoperability

- Interoperability in healthcare is the extent to which various systems and devices can interpret data and display it in a *user friendly way*.
- This entails that data exchange methods will allow information to be shared across hospitals, pharmacies, labs, clinicians and patients, regardless of which vendor is used.
- The main objective is to reform the chaotic and at times dysfunctional nature of information exchange among hospitals.
- Through interoperability, data becomes exceptionally mobile.
- Personal health information, entered into a system once, becomes available to patients, *wherever they are and whenever they need it*.

Reliable Communication

- The communication constraint varies between nodes since the sampling rates required by each sensor are different.
- For example, instead of sending raw electrocardiogram (ECG) data from sensors, we can *perform feature extraction on the sensor, and transfer only information about the particular event*.
- In addition to reducing the high demands on the communication channel, the reduced communication requirements *save total energy expenditures, and consequently increase battery life*.
- A trade-off between communication and computation is crucial for optimal system design.

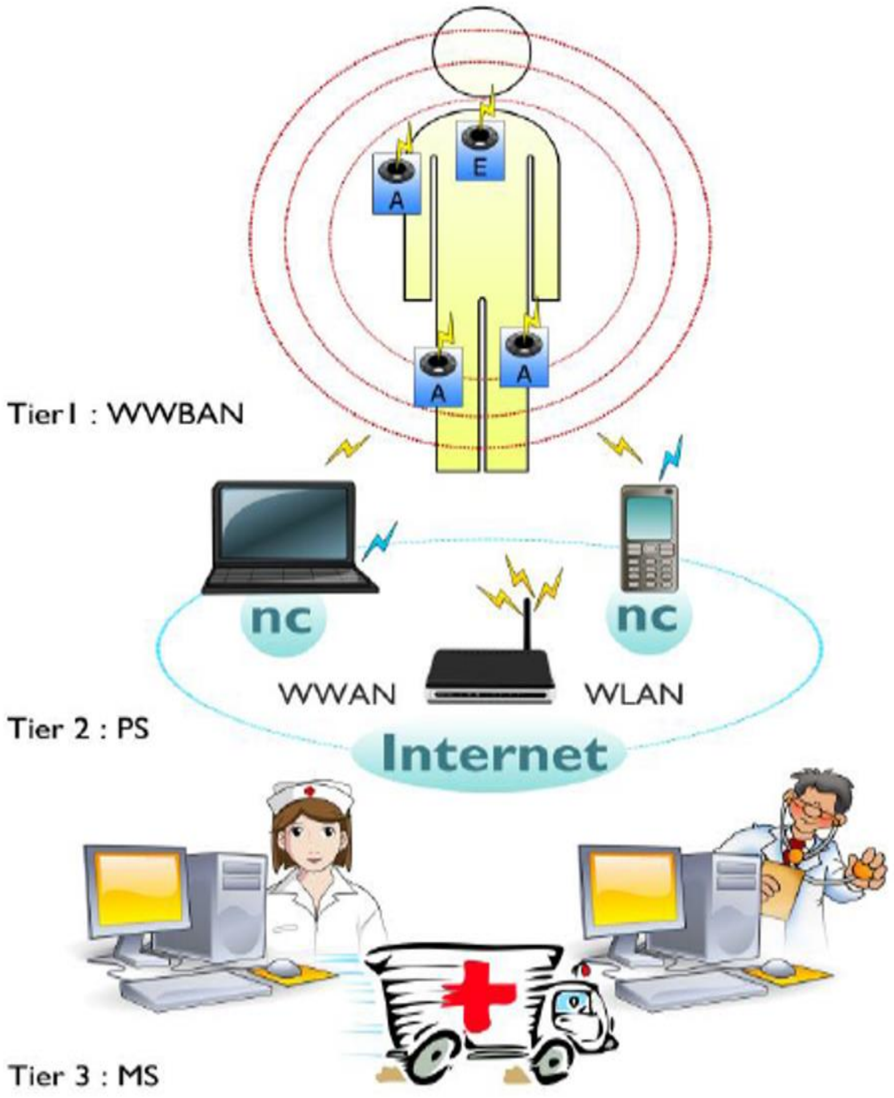


Wearable Wireless Body Area Networks

- To carefully track discrepancies in patients' vital activities and provide feedback for maintaining optimal health status, wearable health monitoring systems have been introduced.

- Upon their integration into the telemedicine system, the wearables turn into alert systems notifying the medical staff when life-threatening changes occur within the patient's body.

- Long-term continuous monitoring can as well be attained as part of the diagnostic procedure.

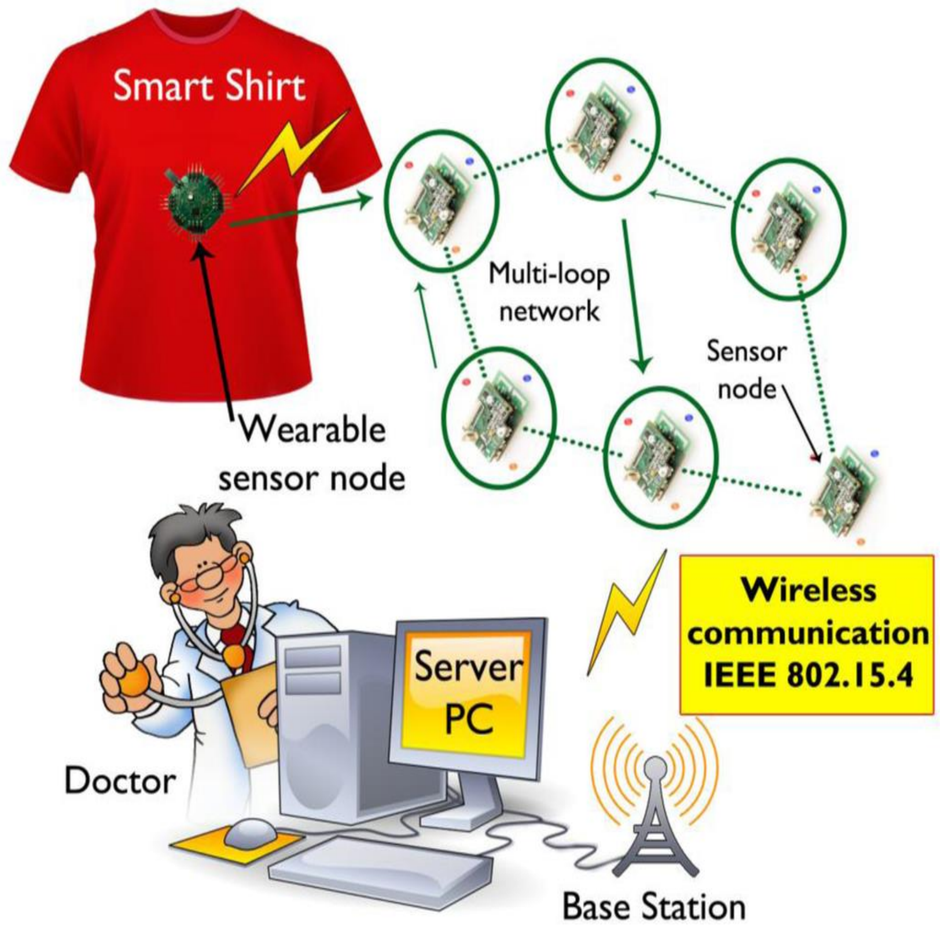


Wearable Wireless Body Area Networks

- "WEALTHY" and "MY Heart" are EU funded projects that use cotton shirts embedded with sensors to measure respiratory activity, electrocardiograms (ECG), electromyograms (EMG) and body posture.

- "NASA" is developing a wearable patch that controls heart rate, blood pressure and other physiological parameters for astronauts.

- The "Nike-Apple" iPod Sports kit as well as the "Lifeshirt" developed by "In Vivo Metrics" are amongst some of the most common commercial wearable prototypes.



Wearable Wireless Body Area Networks

- Wearable networks are considered a key part of a multistage system of telemedicine.
- The architecture of this network includes in its ***first stage*** the nodes that are integrated into the wireless body area network.

  - Each node senses, samples, and processes one or more physiological signals.

- In its ***second stage***, the network architecture constitutes of the personal server application that runs on a personal digital assistant, cell phone or personal computer.

  - It acts as an interface between the user and the medical server enabling network configuration as well as management features.
  - The configuration includes:

    Sensor nodes' registration to sort their type and number
    Initialization to specify the sampling frequency and mode of operation
    Customization to run user-specific calibration and security settings communication

Wearable Wireless Body Area Networks

- The *final stage* includes the access of the medical server via the Internet.

  - This server typically runs up a service that sets up the communication channel to users, collects reports from the user and integrates the data in the medical record of the user.

- Advances in smart technologies gave also rise to a wearable industry which is a key enabler of optimal progressions in our societies.

Wearable Wireless Body Area Networks

- "Smart Stop" by Chrono Therapeutics, is a smart device that aims to help people stop smoking.
  - The device is embedded with sensors that will sense changes in the body and put into motion algorithms that detect the craving of a person for cigarette and nicotine.
  - It will deliver medication to the person so that the craving can be curtailed.

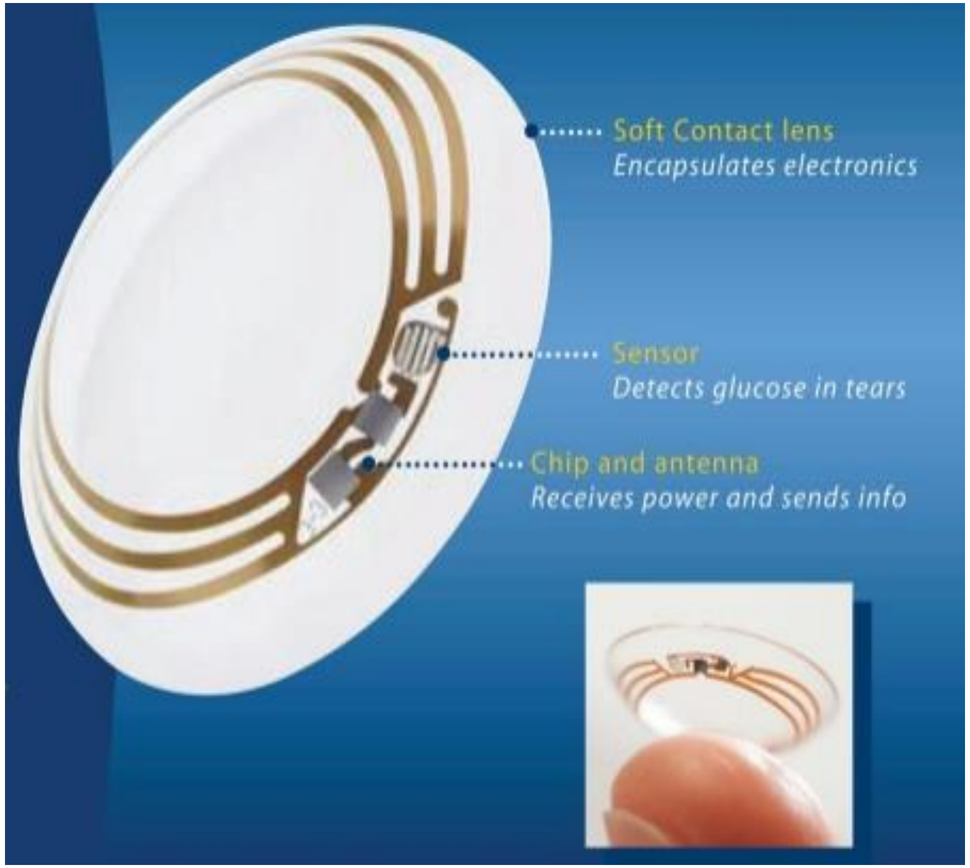
Wearable Wireless Body Area Networks

- "Google Smart Contact Lenses"

  - Google has been able to have smart contact lenses that are made for people who suffer either from diabetes or for those who simply wear glasses.

  - The technology is engineered to take the tears in a person's eye and measure the glucose levels that are present.

  - For people who wear glasses, the lens would be engineered to restore the eye's natural autofocus



Implantable Wireless Body Area Networks

- The interaction between medicine and technology led to the development of genuine diagnostic devices capable of detecting or monitoring pathogens, ions, diseases, etc.
- The integration of rapid advances in areas such as microelectronics, microfluidics, microsensors and biocompatible materials entails the availability of implantable biodevices for continuous monitoring.
- These sensors act as event detectors that carry out faster and cheaper clinical tasks in comparison to standard methods.
- Implantable devices resulted in both improved care and quality of life where early detection of emergency conditions and diseases in patients at risk has been facilitated.
- These sensors actually comprise physical, physiological, psychological, cognitive, and behavioral processes, by reaching inaccessible environments in a reduced response time.

Implantable Wireless Body Area Networks

- Several implantable sensors for in vivo monitoring are currently being developed.
- An example of a well known implantable identification device is an RFID tag developed by “VeriChip Corporation”.
- This device is usually implanted in the upper arm where the medical professionals use the serial number emitted by the VeriChip in order to access a patient’s medical information in a database called “VeriMed”.
- This enables rapid retrieval of vital data even if the person is unconscious or unresponsive during a medical surgery.

Implantable Wireless Body Area Networks

- Other systems enable patients suffering from chronic diseases to live independently.
- As a result of a joint collaboration in Ohio and California, USA, an implantable kidney has been developed.
- This is considered an alternative to dialysis and transplantation based on demonstrated technologies, sound science, and measurable milestones.
- Microelectromechanical Systems (MEMS) have been used to create biocompatible silicon membranes with nano-meter sized pores that can mimic the filtering capacity of the human kidney through cloning.

Implantable Wireless Body Area Networks

- With the parallel development of both on-chip potentiostat and signal processing techniques, substantial progress has been made towards a wireless implantable glucose/lactate sensing biochip.
- The rise of nanotechnology basically resulted in medical research advancements.
- Healthcare is moving quickly towards a future where intelligent medical implants can continuously monitor body conditions and autonomously respond to changes such as infection by releasing anti-inflammatory agents.
- A recent review in WIREs Nanomedicine and Nanobiotechnology, discusses present and prospective implantable sensors incorporating nanostructured carbon allotropes.

Implantable Wireless Body Area Networks

- Various difficulties need to be adhered when dealing with implantable devices.

  - The device must be biocompatible to avoid unfavorable reactions within the body.

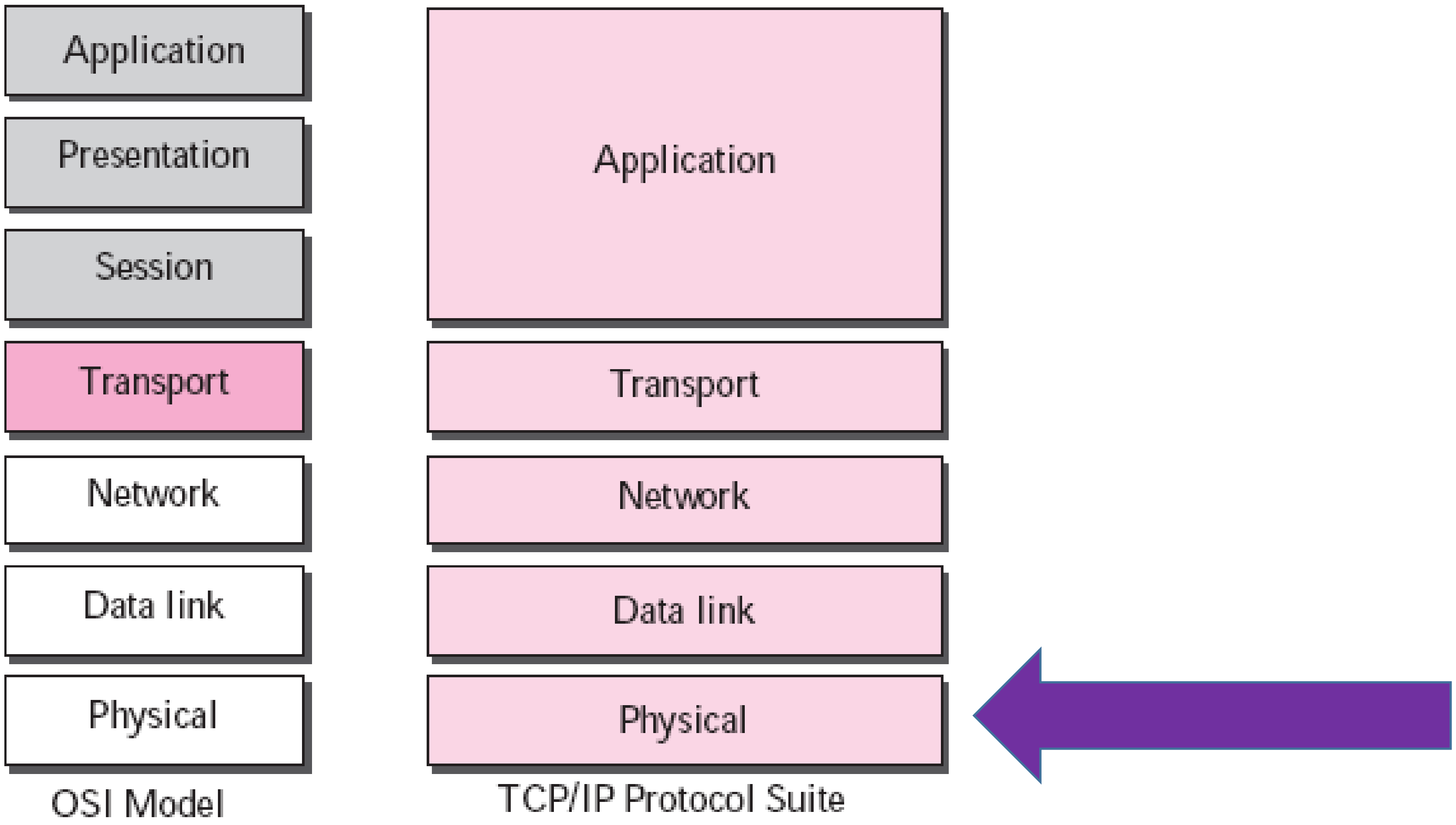
  - The medical device must also provide long-term stability, selectivity, calibration, as well as adequate power in a downscaled and portable device.

Sensors:

- Label-free electrical biosensors are ideal candidates because of their low cost, low power and ease of miniaturization.

- Recent progress in nanobiosensors offers technological solutions in the field of glucose monitoring, pregnancy and DNA testing, as well as microRNA detection.

Challenges of Wireless Body Area Networks



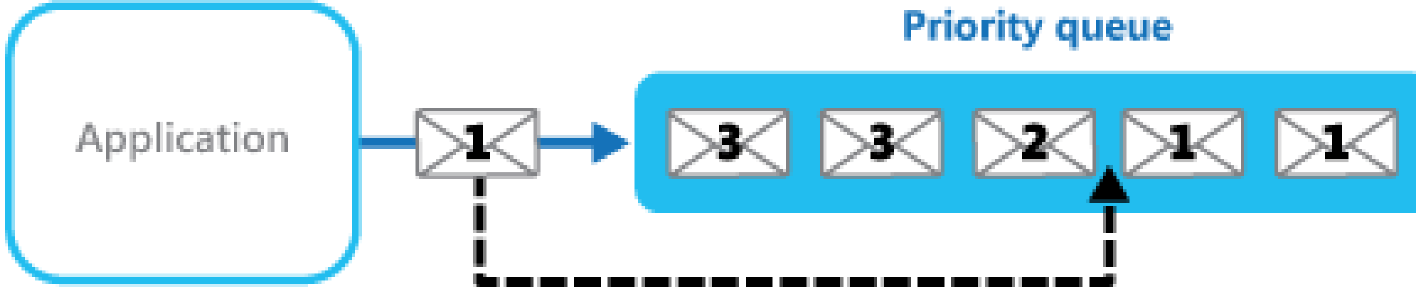
Physical Layer Challenges

- The physical layer suffers from a number of challenges when it comes to implementing wireless body area networks.

- Bandwidth Limitations
- Small Distances between Tx and Rx.
- Receiver Complexity
- Power Consumption is higher in dynamic conditions

MAC Layer Challenges

- For health monitoring applications, Quality of Service (QoS) requirements for emergency traffic should be explored.
- A MAC scheme for healthcare applications which merges a proactive service scheduling into the *802.11.e QoS MAC* to provide the highest channel access precedence for medical emergency traffic has been proposed.
- Under emergency conditions, the delivery of data with a reasonable delay should be guaranteed.
- Emergency data prioritization mechanisms should be developed and fairness among different situations should be considered.
- *The prioritization and fairness mechanisms for vital signal monitoring applications are still open research issues*.



Network Layer Challenges

- One of the open research challenges of wireless health care monitoring systems is the capability of these networks to reduce the energy consumption of computing and communication infrastructure.
- The convergent traffic inherent in wireless sensor networks may cause a choke effect at the node closer to the base station.
- Load balancing routing protocols need to be developed.
- Congestion avoidance and rate control issues become significant when multimedia traffic is encountered.
- For better utilization, these techniques should as well be integrated with data compression techniques.

Transport Layer Challenges

- Reliable data delivery is one of the most important requirements of a wireless healthcare network since it deals with life-critical data.
- Thus, a lost frame or packet of data can cause an emergency situation to be either totally missed or misinterpreted.
- As a result, a cross layer protocol must be designed in order to ensure reliable delivery of different types of traffic.

Application Layer Challenges

- Since the application layer is at the top of the stack, it is expected to have a coordinating mission.
- In this context, the organization of data is critical and requires efficient machine learning algorithms to allow self-learning and autonomous system replacing.

Future of Wireless Body Area Networks

- Reducing the sensor power consumption in a wireless healthcare network.
  - The reliance on less complex data processing techniques.
  - The activation of sleeping mode operation, which allows higher data rates and enables better time synchronization between the transmitted slots.
  - By reducing wireless data transmission, protocol overhead will be decreased, which can be achieved through data compression and transmitting data that is not raw.

- The design of high efficiency miniature antennas for sensor nodes in order to increase the reliability of transmissions and minimize interference.

- The development of energy optimization methods by combining both the link and physical layer functionalities of wireless devices.

Future of Wireless Body Area Networks

- The optimization of each sensor available in the wireless network in accordance with its characteristics using a variable sampling rate.
  - An adaptive communication protocol is to be used to accommodate any differences in the system which will make the system power efficient.

- The design of multiple gateway devices to interface with the existing wireless system in the healthcare area to ensure continued remote monitoring in a wireless body area network.

- Sensors must offer flexibility and integration with third party devices and should not operate as standalone systems in a wireless healthcare network.

Future of Wireless Body Area Networks

- Wireless networks should mimic a hierarchical structure that has objectives like scalability, customized services, and energy efficiency.

- The wireless network should b programmed as a whole rather than programming individual nodes due to the inconsistent behavior of these nodes.

- Topology control algorithms that provide definite, and practical algorithms is required in order to efficiently measure the network performance and offer idealistic mathematical models.

- To design time critical systems, different types of systems such as wireless (mesh) sensor networks are used to carry out control processes in real time.

- The usage of a cognitive sensor network to acquire localized and situated information of the sensing environment by the intelligent and autonomical deployment of sensors.

Conclusion

- An overview of wireless sensors for healthcare has been presented.
- The overview focused on the requirements of wireless networks in the field of healthcare including wearability, security, interoperability, as well as reliable communication.
- It discussed the most recent advancements in both wearable and implantable technologies by shedding light on a number of current applications.
- The review illustrated the challenges and future research areas associated with wireless networks for healthcare applications