Wireless Sensor Network for Wearable Physiological Monitoring

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***Abstract*— Wearable physiological monitoring system consists of an array of sensors embedded into the fabric of the wearer to continuously monitor the physiological parameters and transmit wireless to a remote monitoring station. At the remote monitoring station the data is correlated to study the overall health status of the wearer. In the conventional wearable physiological monitoring system, the sensors are integrated at specific locations on the vest and are interconnected to the wearable data acquisition hardware by wires woven into the fabric. The drawbacks associated with these systems are the cables woven in the fabric pickup noise such as power line interference and signals from nearby radiating sources and thereby corrupting the physiological signals. Also repositioning the sensors in the fabric is difficult once integrated. The problems can be overcome by the use of physiological sensors with miniaturized electronics to condition, process, digitize and wireless transmission integrated into the single module. These sensors are strategically placed at various locations on the vest. Number of sensors integrated into the fabric form a network (Personal Area Network) and interacts with the human system to acquire and transmit the physiological data to a wearable data acquisition system. The wearable data acquisition hardware collects the data from various sensors and transmits the processed data to the remote monitoring station. The paper discusses wireless sensor network and its application to wearable physiological monitoring and its applications. Also the problems associated with conventional wearable physiological monitoring are discussed.**

***Index Terms*— Wearable monitor, physiological parameters, data acquisition hardware, remote monitoring station, wireless sensor network**

I. INTRODUCTION

Wearable physiological monitoring systems uses an array of sensors integrated into the fabric of the wearer to continuously acquire and transmit the physiological data to a remote monitoring station. The data acquired at the remote monitoring station is correlated to study the overall health status of the wearer. The wearable monitoring systems allow an individual to monitor his/her vital signs remotely and receive feedback to maintain a good health status. These systems alert medical personnel when abnormalities are detected. The conventional physiological monitoring system used in hospitals cannot be used for wearable physiological monitoring applications due to the following reasons [1-2].

- The conventional physiological monitoring systems are bulky to be used for wearable monitoring.
- The gels used in the electrodes dry out when used over a period of time, which lead to increase in the contact resistance and thereby degrading the signal quality.
- The gels used in the electrodes cause irritations and rashes when used for longer durations.
- There are number of hampering wires from the sensors to the data acquisition system.
- The signals acquired are affected with motion artifact and baseline wander as the electrodes float on the layer of gel.
- The sensors used in conventional monitoring systems are bulky and are not comfortable to wear for longer durations.

To overcome the above problems associated with the conventional physiological monitoring there is a need to develop sensors for wearable monitoring and integrate them into the fabric of wearer and continuously monitor the physiological parameters. A wearable data acquisition, processing and transmission hardware, which is portable, comfortable to wear for longer durations, and having sustainable battery power and a remote monitoring station is to be developed. The wearable physiological monitoring systems consists of three systems namely (a) vest with the sensors integrated (b) wearable data acquisition and processing hardware and (c) remote monitoring station. In the vest sensors for acquiring the physiological parameters are integrated. The sensors outputs and power cables are interconnected

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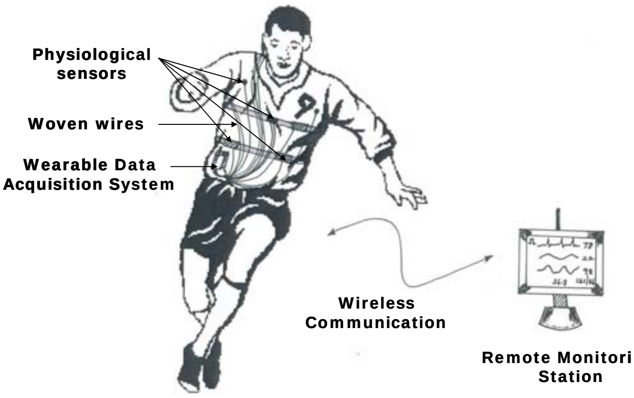

Figure 1. Overall architecture of the wearable physiological monitoring system

to the data acquisition and processing hardware by means of wires routed through the wires woven in the vest. In the wearable data acquisition and processing hardware, the circuits for amplification, filtering and digitization are housed. The digitized and processed data is transmitted wireless to a remote monitoring station. In the remote monitoring station the data is received and displayed in a form suitable for diagnosis. Fig. 1 illustrates the overall architecture of the wearable physiological monitoring system, consisting of a vest with sensors integrated, wearable data acquisition and processing hardware and a remote monitoring station.

A number of wearable physiological monitoring systems have been developed to monitor the health status of the individual wearer. A wearable physiological monitoring system called '*Smart Vest'* to monitor various physiological parameters such as ECG, PPG, heart rate, blood pressure, body temperature and GSR is developed. The acquired physiological parameters are transmitted wireless to a remote monitoring station along with the geo-location of the wearer [3]. A wrist worn wearable medical monitoring and alert system (*AMON*) targeting high-risk cardiac/respiratory patients has been developed to monitor physiological parameters such as ECG, heart rate, blood pressure, skin temperature [4]. *Vivometrics* has developed a wearable physiological monitoring system called '*Life Shirt'* to monitor various cardio-respiratory parameters [5].

A wearable physiological monitoring system for space and terrestrial applications named '*Life Guard'* to monitor the health status of the astronauts in space is developed [6]. The Georgia Tech, *Smart Shirt* characterized as a "wearable motherboard" allows for a variety of vital parameters to be incorporated into the vest, which can be easily and comfortably worn by the soldiers [7]. A textile based wearable system, called *MagIC (Maglietta Interattiva Computerizzata)* for the unobtrusive recording of cardiorespiratory and motion signals during daily life and in a clinical environment on cardiac patients [8].

The *Armband SenseWear* (BodyMedia Inc, Pittsburgh, PA, USA) wearable body monitor has been used to study bodily movement and energy expenditure in normal subjects and Chronic Obstructive Pulmonary Disease (COPD) subjects [9]. The *WEALTHY* (Wearable Health Care System) involves wearable textile interfaces integrating sensors, electrodes and connections realized with conductive and piezoresistive yarns. The *WEALTHY* system is made up of a sensorized cotton or lycra shirt that integrates carbon-loaded elastomer strain sensors and fabric bio-electrodes, enabling the monitoring of respiration, ECG, EMG, body posture and movement [10]. *MyHeart* wearable monitoring system focuses on integration of unobtrusive sensors into everyday garments and miniaturized on-body electronic modules for data processing and storage with dedicated software for data analysis like ECG preprocessing and motion artifact detection, computation of heart rate and heart rate variability parameters [11].

A number of wearable physiological monitoring systems have been put into practical use for health monitoring of the wearer in hospital and real life situations and their performances have been reported [12-17]. Varying degrees of success have been reported and the percentage failures in the outdoor use are high. The drawbacks associated with the conventional wearable physiological systems are

- The cables woven into the fabric to interconnect the sensors to the wearable data acquisition hardware pick up interfering noises (e.g. 50 Hz power line interference). The wires integrated into fabric act like antennas and can easily pick up the noises from nearby radiating sources.
- The sensors once integrated into the fabric, its location cannot be changed or altered easily.
- The power required for the sensors to operate is to be drawn from the common battery housed in the wearable data acquisition hardware and are routed through wires woven in the fabric.
- Typically these systems consist of a centralized processing unit to digitize, process and transmit the data to a remote monitoring system. The processor is loaded heavily to perform multi-channel data acquisition, processing and transmission of data.
- The cables from the vest interconnecting the sensors can get damaged very easily due to twisting and turning of the cables, while the wearer is performing his routine activity.

To overcome the above issues related to wearable physiological monitoring, the individual sensors integrated into the vest can be housed with electronics and wireless communication system to acquire and transmit the physiological data. The recent advances in the sensors (MEMS and Nanotechnology), low-power microelectronics and miniaturization and wireless networking enable Wireless Sensor Networks (WSN) for human health monitoring. A number of tiny wireless sensors, strategically placed on the human body create a wireless body area network that can monitor various vital signs, providing real-time feedback to the user and medical personnel [18-22]. A multi-channel, bidirectional and implantable bio-telemetric platform for real time *in-vivo* monitoring of several physiological monitoring systems have been developed [23].

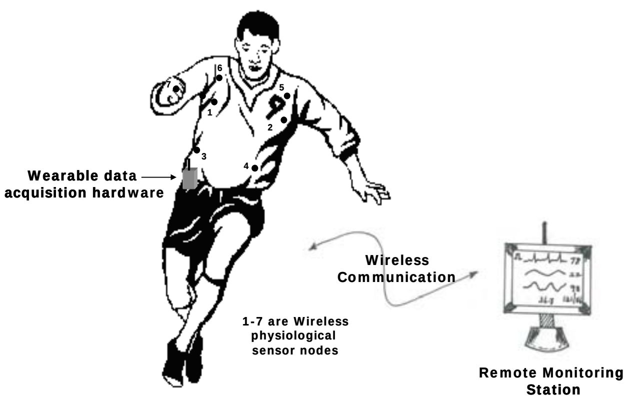

Figure 2. Overall architecture of the wireless sensor network based wearable physiological monitoring system

Fig. 2 illustrates the architecture of a WSN based wearable physiological monitoring system. Wireless Sensor Networks (WSN) consists of a large number of small nodes, which have built-in computing, power, sensors to acquire physiological data from the wearer and wireless transmission and reception capability. A wireless sensor network for smart electronics shirt has been developed which allows the monitoring of individual biomedical data and is transmitted wireless for further processing using a wireless link [24]. A number of wireless ECG monitoring systems based on conventional electrodes have been developed [25-28], a two lead wireless ECG and oxygen saturation in blood monitoring systems is developed [29]. A wireless body sensor network with embedded intelligent motion sensors for computer assisted physical rehabilitation is developed to give feedback to the user and generate warnings based on the users state, level of activity and environmental conditions with data transmission capability to medical servers via internet [30]. A personal health monitor based on a wireless body area network (BAN) integrated with intelligent sensors for psychophysiological evaluation of military members undergoing intense training by measuring heart-rate variability (HRV) to quantify stress level prior to and during training as well as to predict stress resistance is developed [31]. The project *CodeBlue* describes the wireless medical sensor network hardware and software platform to medical monitoring of individuals [32]. Patient monitoring over the wireless infrastructure oriented ad-hoc network has been investigated [33-34]. These systems are useful in transmitting the medical over larger distances and do not discuss about the applications of wearable physiological monitoring.

DEBEL has gained sufficient expertise during the development of a wearable physiological monitoring system named as *Smart Vest* [3]. The development has culminated in the form of *Smart Vest* with sensors integrated to sense, process, store and transmit the physiological data. The developed system made use of sensors integrated into the fabric interconnected by woven wires, and interfaced to a wearable data acquisition and processing hardware. To address the various issues and problems encountered during the development of the *Smart Vest*, the development of wireless sensor network for wearable physiological monitoring has been initiated.

The objective of this paper is to discuss a conceptual design of a wearable physiological monitoring system based on wireless sensor network to monitor a number of physiological parameters. The physiological parameters to be monitored are Electrocardiogram (ECG), Electromyogram (EMG), Electroencephalogram (EEG), Oxygen Saturation in blood (SaO2), body temperature, systolic and diastolic blood pressure, respiratory rate, Galvanic Skin Response (GSR) and movement of the wearer recorded by an accelerometer. The acquired physiological signals are preprocessed at each node and transmitted to the wearable data acquisition hardware (sink node) for further processing and transmitted wireless to a remote monitoring station. The paper also discusses the architecture of the WSN for wearable physiological monitoring, protocols, security issues and power requirements.

II. MATERIALS AND METHODS

A. Physiological Parameters

The physiological parameters that are monitored are Electrocardiogram (ECG), heart rate derived from ECG signals by determining the R-R intervals, blood pressure, body temperature, Galvanic Skin Response (GSR), Oxygen saturation in blood (SaO2), respiratory rate, Electromyogram (EMG), Electroencephalogram (EEG) and three axis movement of the subject measured using an accelerometer. Table 1 illustrates the specifications of the physiological signals being monitored [35-36].

Physiological Parameter	Specifications
Electrocardiogram (ECG)	Frequency: 0.5Hz – 100 Hz Amplitude: 0.25 – 1mV
Electromyogram (EMG)	Frequency: 10Hz - 3KHz Amplitude: 50μV – 1mV
Electroencephalogram (EEG)	Frequency: 0.5Hz - 100Hz Amplitude: 1μV – 100μV
Blood Pressure (BP)	Systolic: 60 - 200mmHg Diastolic: 50 – 110mmHg
Body Temperature	32^oC – 40^oC
Galvanic Skin Response (GSR)	0 – 100 KΩ
Respiratory Rate (RR)	2 – 50 breaths/min Frequency 0.1 – 10Hz
Oxygen Saturation in Blood (SaO2)	0-100%
Heart Rate (HR)	40 – 220 Beats per minute

TABLE – I.
SPECIFICATION OF VARIOUS PHYSIOLOGICAL PARAMETERS MONITORED

B. Wireless Sensor Network Architecture for Physiological Monitoring

A network is formed when a set of small sensor devices that are deployed in an “ad hoc fashion” with no predefined routes, cooperate for sensing a physical

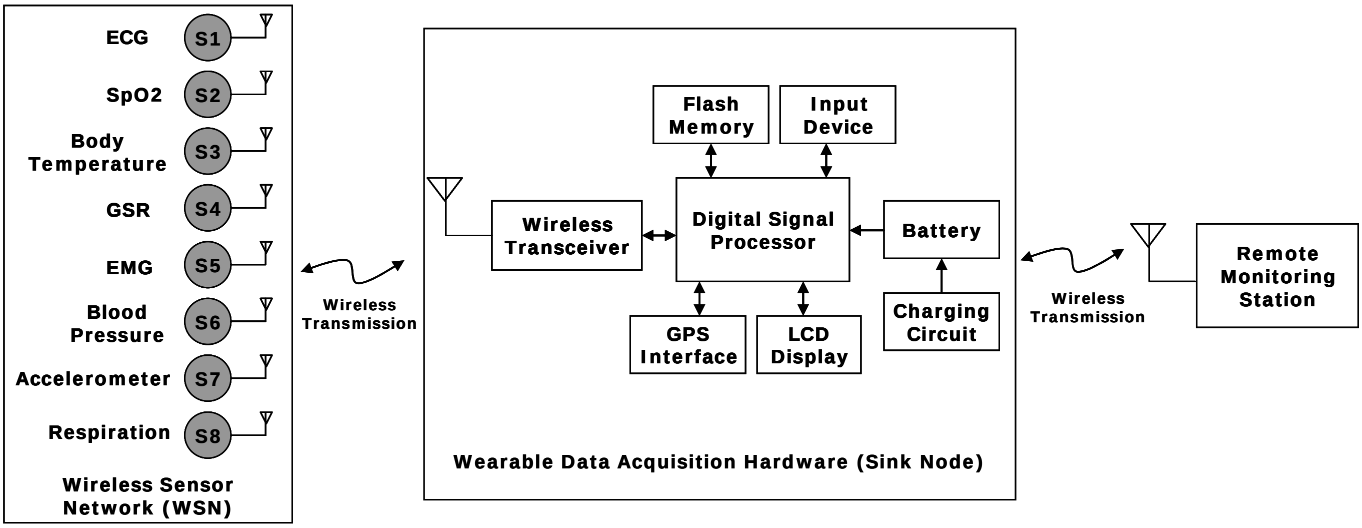

Figure 3. Overall architecture of Wireless Sensor Network (WSN) consisting of sensor nodes, sink node and remote monitoring station

phenomenon. A Wireless Sensor Network (WSN) consists of base stations and a number of wireless sensors which are simple, tiny in size, inexpensive, and a tiny battery-powered. The recent advances in the processor performance, low power consumption, small size has made the realization of WSN. With the advances in materials technologies, novel sensing materials for many sensing applications has come into existence. The wireless transceivers for wireless devices are reducing in size, less expensive, consume less power and smaller antenna size. The power source improvements in batteries, as well as passive power sources such as solar or vibration energy are expanding application options. The WSN for monitoring the physiological monitoring consists of three modules namely sensor nodes, wearable data acquisition and processing hardware (sink node) and remote monitoring station. Fig. 3 illustrates the detailed block diagram of the wireless sensor network.

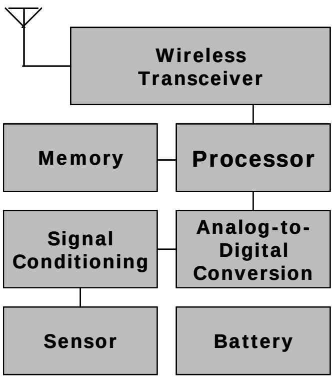

Figure 4. Block diagram of the wireless sensor node

1) Sensor Node

The sensor nodes are responsible for acquiring the physiological data and transmitting it to the wearable data acquisition hardware (sink node). There are a number of sensors nodes strategically placed at various location on the wearer to acquire and transmit the physiological data to the sink node. The sensor nodes are tiny in size, inexpensive, and have a miniature battery which can last for longer durations. The sensor nodes have limited power, computing and communication capability. The various components of a sensor node are sensing element, signal conditioning, analog-to-digital converter (ADC), processor, wireless transceiver, flash memory, battery and antenna. Fig. 4 illustrates the block diagram of the various components of the sensor node. The sensors senses the physiological data and is preconditioned (amplification and filtering) to levels suitable for digitization. The digitized data is transmitted to the sink node.

A processor is programmed to control and coordinate the activities of the sensor node for data acquisition, establishing communication with the sink node and putting the node into sleep and wakeup modes. The sensors nodes do not have IP address, but may have their own identifiers, but are capable of recognizing themselves. In the sensor nodes the computations of data is preferred over communications because of power requirements, data transmission costs typically dominate energy consumption of sensor node. Nodes can have temporary failures or permanent failures, which will lead to the loss of data and lead to misdiagnosis. The sink node should access the status of the failed sensor node and self organize. The deployment of sensor node in the wearable monitoring system is done at chosen points. Addition of nodes at anytime during use of the sensor network to replace the failed nodes, or to get an additional physiological data is feasible.

2) Wearable Data Acquisition Hardware

The wearable data acquisition hardware also known as the sink node is responsible for interacting with the sensor nodes. The data from the sensor nodes are received, processed and transmitted to the remote monitoring station. The wearable data acquisition hardware is based on processor having digital signal processing capability. The sink node consists of various modules such as antenna, transceiver, processor, flash memory, input unit, display and battery with charging circuit. The received data are conditioned and further processed to remove noises and parameters are computed. The medical data is time stamped and stored in memory as well and transmitted to a remote monitoring station for further analysis. The wearable data acquisition hardware is powered by a rechargeable battery to operate for minimum 8-12 h duration.

3) *Remote Monitoring Station*

The physiological data from the wearable data acquisition and processing hardware is transmitted to the remote monitoring station. In real life situations there will be a number of wearable data acquisition devices communicating the data to the remote monitoring station. A typical example is monitoring the health status of the soldiers in battle field. The remote monitoring station is generally located far away from the individual wearers. The data of the individual wearers are displayed at the remote monitoring station. At the remote monitoring station, the physiological parameters of the individual wearers are analyzed and automatic alarms are generated.

C. *Wireless Sensor Network Architecture*

The interconnectivity between the sensors nodes can be established by different communication modalities, such as radio, light, laser, Infra Red (IR), sound, inductive or capacitive coupled. Of all the communication modalities listed, the radio waves based is widely used due to its unique features such as, they do not require a free line of sight, they can penetrate through walls and objects very easily, their communication over shorter ranges can be established using very low powers and relatively small size antennas. In the radio based communications there are two common forms of network exists, which are infrastructure-based networks and ad hoc networks. The ad hoc networks are best suited for the wearable physiological monitoring applications due to its unique features [33-34].

To make WSN feasible for all kinds of applications at lower cost, it is necessary that topology, medium access control and security be as simple as possible and consumes less power. The topology of the network decides the characteristics of the sensors network. In a star topology, all the sensor nodes communicate to the sink node in a single hop, but with a failure of the sink node, the network fails. In case of a multi-hop network, the sensor nodes makes more than one hop before communicating with the sink node. The issues associated with the multi-hop are the delay in the data reaching the destination, complex routing algorithm, latency and data handling capability of a particular node. The effective wireless coverage of a sensor node is important to have connectivity between the sensor nodes and the sink node to effectively collect, process and transmit the data to a remote monitoring station. The drop in connectivity between the sensors nodes and sink nodes lead to loss of vital medical data.

Depending on the application of the sensor network, the data delivery model to the sink can be continuous, event-driven, query-driven and hybrid [37]. In the continuous delivery model, each sensor sends data periodically. In event-driven and query driven models, the transmission of data is triggered when an event occurs or a query is generated by the sink. Some networks apply a hybrid model using a combination of continuous, event-driven and query-driven data delivery. For physiological monitoring application a hybrid model of data delivery will be suitable, wherein, some of the parameters like ECG, EEG, GSR, body temperature, SaO2 and heart rate will be monitored continuously and parameter like blood pressure will be monitored periodically.

D. *Power*

The sensor nodes are independent devices, their energy and other resources are limited by size and cost constraints. Varying size and cost constraints directly result in corresponding varying limits on the energy available (i.e., size, cost, and energy density of batteries or devices for energy scavenging), as well as on computing, storage and communication resources [38].

Each sensor node has limited energy supply and the nodes may use a rechargeable battery or can be self-powered. In the application of wireless sensor networks for wearable physiological monitoring, the conservation of power is important. Some of the vital physiological data are to be monitored continuously and some physiological parameters to be acquired and transmitted at regular intervals and few of them to be acquired and transmitted on need basis. Some of the sensor nodes are active continuously and some are inactive state (sleep). During the sleep state the current consumption of the node has to be very low as possible. The power consumption can be managed in many ways, one is to perform the task as fast as possible (consume very high current in a short time) and return the sensor node to sleep mode, and other method is to transmit the data at very slow rate by consuming very low currents (current consumption is proportional to speed). The transmission power of a wireless radio is proportional to distance squared or even higher order in the presence of obstacles. The sensor nodes for physiological monitoring are located very close to the sink node, and the power requirements for data transmission should be very low.

The WSN can use rechargeable and non-rechargeable batteries. In very harsh environments it is very difficult to recharge a battery, so non-rechargeable battery is preferred. Alkaline batteries have a wide voltage range and large physical size, but a lithium battery provides a constant voltage supply but with very low nominal discharge currents. Nickel Metal Hydride can be recharged but with a significant decrease in energy density. The power management can be carried out by Dynamic Power Management (DPM) or Dynamic Voltage Scheduling (DVS) [39]. In DPM technique unused devices can be shut down and activated when required, but this method requires the support from the operating system and stochastic analysis to predict future events. In DVS power can be varied to allow for a non-deterministic workload. The network lifetime can be maximized by managing the power consumption of each node so that global network connectivity can be maintained. Topology control algorithms to maintain network connectivity while reducing energy consumption and improving network capacity [40]. Nodes will adjust their power consumption according to their individual data processing and communication requirements.

E. *Security Threats in WSN*

Wireless sensor networks for physiological applications vary in size and are deployed over the different regions of body of an individual. There are concerns on security issues in these networks, as the data being monitored is the health status of the individual. Sensor nodes used to form these networks are resource-constrained, which make security applications a challenging problem [41]. To ensure the security of the data being monitoring, the data acquired from each sensor nodes can be encrypted and sent to the sink node, but the encryption and decryption mechanisms has to be very simple and energy efficient. The data are also vulnerable to external attackers, by injecting errors in the routing information, replaying old routing information, distorting routing information or sending malicious information. The data is also subjected to jamming, tampering, Sybil attack, collision, etc [42-44].

The confidentiality requirement is needed to ensure that medical data is well protected from others getting an access to it and not revealed to unauthorized persons while the data is traveling from the sensor nodes to the sink node. The various participants in the network has to be authenticated, by establishing the identity of the user and verifying that the data send is a valid data. Also the integrity of the medical data needs to be ensured as the data being exchanged is medical data.

F. *Wireless Protocols*

Wireless sensor networks are inherently plagued by problems of node failure, interference to communications from environmental noise and energy limitations in the nodes. The wireless sensor network has to meet certain quality-of-service (QoS), such as real-time constraints, such as reporting an occurrence of event within a certain period of time, robustness, tamper-proof, resistant to eavesdropping, detection of presence of network [45,38]. Several routing protocols have been proposed for the problem of routing data in sensor networks. Almost all of the routing protocols can be classified as data-centric, hierarchical or location based, although there are few distinct ones based on network flow or quality of service (QoS) awareness [46-47]. The routing protocols also should be energy aware, as some sensor networks use multi-hop paths in order to minimize the total transmission power [48-49]. In almost all the sensor networks data are routed towards a single sink, hops that are close to the sink will become heavily involved in packet forwarding, and their batteries get depleted quickly [50]. The data centric protocols are query based, in which the sink node sends queries to sensor node and waits for data from the sensor. Hierarchical protocols aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy. Location based protocols utilize the position information to relay the data to the desired regions rather than the whole network.

In the wearable monitoring application using the WSN, the sensor nodes are stationary and at the most 15-20 sensor nodes are deployed. The sensors are distributed very close to the sink node, the data centric approach is better suited to communicate between sensor nodes and sink node. The sink node sends queries to the sensor nodes and waits for data from the sensors. The data received from various sensor nodes are further processed at the sink nodes and transmitted to the remote monitoring stations. The model takes into account the energy consumption associated to each packet transmission and reception. When the node energy level goes down to zero, the node dies out and there are consequently no possibility of transmitting or receiving a packet.

III. DISCUSSION

Wearable physiological monitoring systems are intelligent medical monitoring devices, which provide real-time feedback to the wearer or remote monitoring station. The wearable physiological monitoring by means of integrating sensors and wires integrated into the fabric of the wearer has a number of drawbacks. To overcome the issues discussed earlier, each physiological sensor is integrated with the sensors and its processing electronics and a wireless transceiver to form a network of sensors.

A wearable WSN of physiological sensors integrated into a vest of the individual acquires the data and transmits to a remote monitoring station continuously, where the health status of the individuals is monitored remotely. These systems are capable of monitoring the health status of individuals who perform very high risk jobs like soldiers in a battle field, fire fighters, mine workers, etc. Also these systems will be useful for monitoring the health status of the elderly people at home. The data collected from the wearer using the wearable physiological monitoring systems should be kept private and during transmission the data should be encrypted and be secured. The wearable physiological monitoring systems must give reliable recordings of medical data compared to the conventional physiological monitoring systems. They are supposed to function as long as 48-72 h for continuous monitoring, without any failures, the device should have data stored with time stamps [1].

Continuous monitoring with early detection has likely potential to provide patients with an increased level of confidence, which in turn may improve quality of life. In addition, ambulatory monitoring will allow patients to engage in normal activities of daily life, rather than staying at home or close to specialized medical services. One of the most critical issues in wireless sensor network is the limited availability of energy on network nodes, hence making good use of energy is necessary to increase network lifetime [51]. Each sensor node has limited energy supply to cater for the sensing, data processing, data storage and transceiver and the nodes may or may not have the capability to recharge. The maximum energy is consumed by communication system, so the most energy-conserving communication protocol is to be used [52]. The bandwidth is limited and must be shared among all the nodes in the sensor network. Spatial reuse is essential and efficient local use of bandwidth is needed [42]. Wireless sensor network for physiological monitoring are likely to suffer from the problems of node failures, noise interferences from external sources, since physiological signals are very low in amplitudes and frequencies, interfering noises can easily get added. Reliable and efficient communication of the acquired data is very important [53], to avoid any loss of vital data during diagnosis.

The current technological developments in the field of microelectronics, Micro Electromechanical System (MEMS), nanotechnology will enable the development of miniature sensors to acquire, process, digitize and transmit the physiological signals using very low powered batteries. Also the sensors will be placed strategically at various locations of the human body as small patches and will communicate with the wearable data acquisition and processing hardware and also can be worn for extended periods of time.

The WSN uses a number of sensors using RF energy to communicate with the sink node continuously. The various biological effects of the electromagnetic radiations used in this frequency ranges due to prolonged exposure were investigated and reported [54-55]. WSN are being investigated for use in a variety of applications, such as military (battle field surveillance, enemy/friendly forces monitoring and tracking, biological and chemical attack detection), environmental applications (forest fire and flood detection, seismic activity, monitoring of drinking water and level of air pollution), health applications (monitoring of human physiological data), home applications (intrusion detection, home automation), commercial applications (inventory control, material fatigue, monitoring of product quality), climate control in large buildings and habitat monitoring.

In this paper, the concept of the WSN for wearable physiological monitoring was discussed. The architecture of WSN, protocols, security of data and power requirements for longer durations of operations were also discussed.

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