QoS in Body Area Networks: A survey

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Body Area Networks (BANs) are becoming increasingly popular and have shown great potential in real-time monitoring of the human body. With the promise of being cost effective, unobtrusive, and facilitating continuous monitoring, BANs have attracted a wide range of monitoring applications, including medical and healthcare, sports, and rehabilitation systems. Most of these applications are real-time and life-critical, and require a strict guarantee of Quality of Service (QoS), in terms of timeliness, reliability, etc. Recently, there have been a number of proposals describing diverse approaches or frameworks to achieve QoS in BANs (i.e., for different layers or tiers, different protocols). This survey put these individual efforts into perspective and presents a more holistic view of the area. In this regard, this article identifies a set of QoS requirements for BANs applications and shows how these requirements are linked in a 3-tier BAN system, and presents a comprehensive review of the existing proposals against those requirements. In addition, open research issues, challenges, and future research directions in achieving these QoS in BANs are highlighted.

CCS Concepts: •**Computer systems organization** → **Embedded and cyber-physical systems;** •**Networks** → Network reliability;

Additional Key Words and Phrases: Body Area Networks, QoS, Healthcare, Medical Care, Cloud Computing

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1. INTRODUCTION

BANs[1] or Body Sensor Networks (BSNs) are wireless networks of wearable computing devices placed on, in or around human bodies. These devices monitor physiological signals and motion of the wearers for medical, personal entertainment, and other applications and purposes [IEEE 2013]. These applications, especially medical and healthcare applications will improve quality of life of people by providing continuous and remote monitoring without interrupting their daily lifestyle, minimizing the risks of infections significantly, and reducing cost of hospitals and patients. However, challenges, including QoS, standardization, and social issues faced by BANs need to be resolved [Patel and Wang 2010; Chen et al. 2011] for wider applications of BANs.

Generally, medical and healthcare applications are mission critical, and they need to be reliable in terms of QoS [Ameen et al. 2008; Hanson et al. 2009a; Chen et al. 2011;

[1]BANs are also called Body Sensor Networks (BSNs), Wireless Body Area Networks (WBANs) and, to a lesser extent, Body Area Wireless Sensor Networks. So WBANs, BSNs or BANs are interchangeable in most cases.

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Zhou et al. 2011]. Moreover, these applications require system-wide QoS support. In critical applications, lack of QoS support in one of the 3-tiers of a BAN (Figure 1) or even in a protocol may make a BAN application ineffective. For example, failure to obtain fresh and correct medical data, due to any tier or protocol, might lead to wrong treatments and disastrous consequences [Darwish and Hassanien 2011].

To date, many QoS-aware protocols and frameworks [Ameen et al. 2008; Zhou et al. 2008; Otal et al. 2009; Razzaque et al. 2011; Zhou et al. 2011; Jacob and Jacob 2015] have been proposed for BANs. Also, many surveys [Movassaghi et al. 2014; Dangi and Panda 2014; Hanson et al. 2009b; Cavallari et al. 2014; Acampora et al. 2013; Seyedi et al. 2013; Javadi and Razzaque 2013; Filipe et al. 2015a] have reviewed different aspects (i.e., opportunities and challenges, communications, security and privacy, intrabody communication) of BANs/WBANs, but there is no such survey on QoS. Movassaghi et al. [Movassaghi et al. 2014], have reviewed ongoing research in WBANs in terms of system architecture, address allocation, routing, channel modeling, physical (PHY) and media access control (MAC) layers, security, and applications. They also have identified many challenges, including QoS. Acampora et al. [Acampora et al. 2013] have explored the application of ambient intelligence (AmI) in healthcare from various perspectives (e.g., physical or mental disabilities, chronic disease, or rehabilitation). The authors in [Dangi and Panda 2014; Hanson et al. 2009b; Cavallari et al. 2014] have identified many opportunities and challenges in WBANs, including communication level (e.g., PHY, MAC layers) QoS. Although, many existing surveys, including [Movassaghi et al. 2014; Hanson et al. 2009b; Cavallari et al. 2014], have highlighted the importance of QoS in BANs/WBANs, but these articles rarely survey or partially survey the area. On the contrary, QoS-specific articles [Ameen et al. 2008; ODonoghue et al. 2008; Thapa and Shin 2012; Masud 2013; Bangash et al. 2014a] provide partial reviews of the area. For example, Ameen et al. [Ameen et al. 2008] have focused on the QoS requirements for different data delivery models, and O'Donoghue et al. [ODonoghue et al. 2008] have analyzed data quality of patients' sensors. The survey in [Thapa and Shin 2012] has reviewed only MAC protocols in terms of their QoS support. On the contrary, QoS-aware routing is one of the many concerns of [Bangash et al. 2014a].

Considering the importance of QoS in various applications of BANs, this article takes a holistic view of QoS in BANs and (1) identifies the QoS requirements of different BAN applications (Section III), (2) based on the identified requirements, presents a comprehensive review of the existing QoS-aware mechanisms or protocols (layer's perspective) and frameworks in BANs focusing on current, state-of-the-art research (Section IV), and (3) outlines open research challenges and recommends future research directions (Section V).

2. OVERVIEW OF BANS

Architecture of a BAN depends on its application. Generally, BANs/WBANs applied in medical and healthcare applications consist of a 3-tier architecture [Otto et al. 2006; Natarajan et al. 2007a] (Figure 1). Three tiers are: (1) Intra-BAN-Communication, (2) Inter-BAN-Communication, and (3) Beyond-BAN Communication. The main components of tier 1 are sensor nodes or sensors placed on human body as tiny patches, or hidden in users' clothes, or in human body, and embedded in wearable devices (e.g., smart watch). These sensors or devices gather necessary physiological and other signals, and send them directly or via other sensor nodes to a Personal Server (PS) or a Network Coordinator (NC). The PS (e.g., smartphone or tablet or laptop), in tier two, processes these measurements and presents the information to the BAN user or directly sends to the top tier components. The PS also sends the care or service providers' feedback or decision to service consumers, i.e., patients. The components in tier 2 and 3 can communicate with each other through a cellular network or the Internet. The top tier includes a medical server [Otto et al. 2006; Natarajan et al. 2007a] or a cloud server [Shimrat 2009; Rolim et al. 2010; Ahmed and Gregory 2011; Mohapatra and Rekha 2012] that further processes and stores data collected. Finally, service providers (i.e., clinic, hospital) in tier 3 work on the processed data or information and take necessary actions, including sending feedback to users (such as change of medication). The top tier also includes family members, insurance companies, and others related stakeholders.

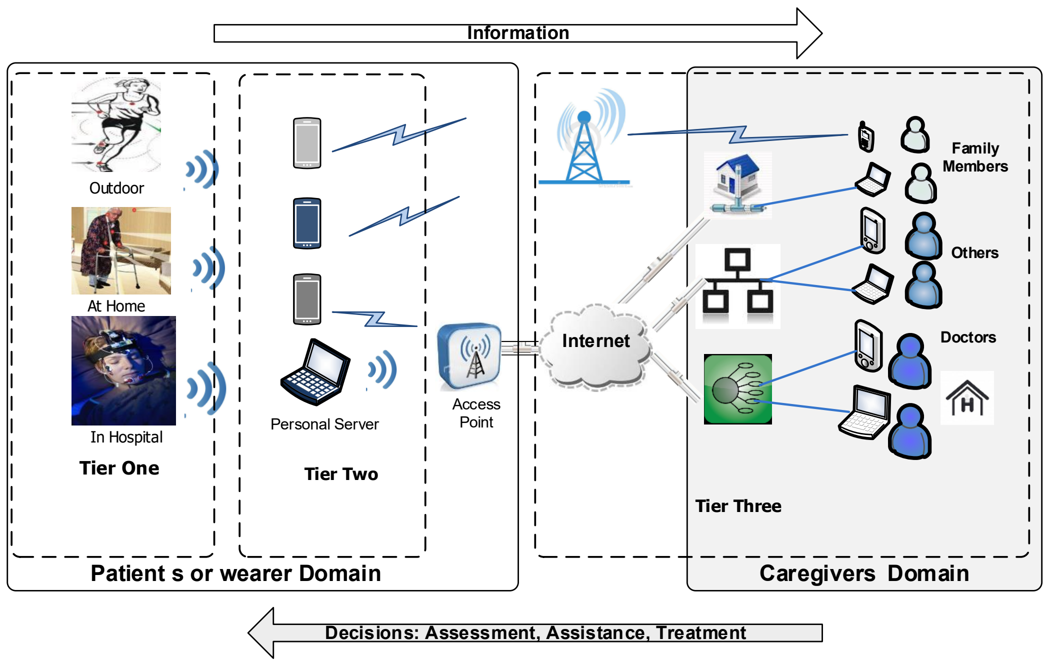


Fig. 1. Wearable health monitoring system: a 3-tier BAN architecture.

2.1. Characteristics of BANs

A number characteristics of BANs, including resource-constrained, real-time and heterogeneous traffic, and unreliable links are inherited from Wireless Sensor Networks (WSNs). Other characteristics of BANs are mainly influenced by human body (e.g., dynamic pathloss) and BANs' applications (e.g., heterogeneity in traffic, criticality) [Chen et al. 2011; Munir et al. 2007].

Resource-constrained: Embedded computing and sensors in WSNs, including BANs require a small device form factor, which limits their processing, memory, communication, and battery capacity. In such resource-constrained systems, traditional QoS-aware protocols, especially routing and MAC protocols are unsuitable.

Dynamic traffic patterns: In traditional networks, QoS support often depends on a certain periodicity of the data traffic. On the contrary, traffic patterns in BANs are dynamic (e.g., bursty or periodic or no traffic), which makes data delivery in BANs with appropriate QoS, such as timeliness a challenging task.

Network dynamics: Network topology of BANs can change dynamically because of node mobility, node failure, disrupted wireless connectivity, and joining of new nodes.

It is difficult to maintain a stable network in such a dynamic environment and support QoS in most BANs applications.

Data redundancy: Redundancy in sensor data gathering is a very common issue. Sensing, processing, and communication of redundant sensor data consume a significant amount of precious and limited energy of sensor nodes. Data compression (e.g., aggregation, predictive coding, compressed sensing) can minimize data redundancy and offer energy efficiency. However, data compression may increase latency and distortion, which complicates QoS design [Razzaque et al. 2013].

Heterogeneous traffic: It is often required to get access to heterogeneous data collected by different types of sensors with different sampling rates. This makes QoS support in BANs a complex and challenging task.

Criticality: In many applications, such as medical and healthcare, most sensors readings are critical and require real-time responses. Mechanisms are necessary to differentiate sensor readings based on criticality or importance and setup a priority structure.

Dynamic Pathloss: In and on body wireless communications face dynamic pathloss [Roelens et al. 2006], which, along with the mobility of the wearer/patient, increase packet loss probability in BANs.

Context: Environmental and users' context in most applications of BANs pose additional challenges to support QoS. Effective bandwidth of these systems usually degrades because of the presence of Radio Frequency (RF) emitting devices around a human body [Zhou et al. 2008]. For example, in hospital environments, very low Signal-to-Noise-Ratio (SNR) values are expected. Also, user's activity dependent context can play an important role in setting QoS requirements. All these issues can cause delays and increase power consumption. Context-aware adaptive mechanisms are necessary to provide QoS support in such harsh and dynamic environments [Calhoun et al. 2012].

2.2. Services and Applications of BANs

BANs are expected to enable a variety of services, including medical and healthcare services. These services can be categorized into four different groups [Pansiot et al. 2010; Cao et al. 2009; Ullah et al. 2012; Hadjidj et al. 2012; Islam et al. 2015; Jon Mark et al. 2013]: (i) acute care, (ii) post-acute care or rehabilitation, (iii) chronic care, and (iv) prevention and wellness. Figure 2 summarizes these services in terms of their supported key applications, criticality, real-time response, and QoS requirements. In general, acute and post-acute care services include critical applications (e.g., life-threatening injuries, acute appendicitis). In these applications BANs need to offer relevant, accurate (i.e., Bit Error Rate (BER) ¡10^{-10}) and real-time (i.e., latency as low as 10ms) information at the time of the treatment. On the other hand, chronic care service offers effective management of various chronic diseases (e.g., heart disease, stroke, cancer, diabetes, arthritis) to reduce acute or critical events for patients. BANs used for these patients need to monitor their health condition continuously and accurately and send them to caregivers in real-time (hard/soft [Kopetz 1997] depending on a disease and its condition, latency ¡250ms) manner to avoid acute or critical conditions. Generally, prevention and wellness services are for non-critical or healthy individuals and individuals at risk for specific chronic diseases (e.g., patients with pre-diabetes). BANs for these applications need to collect different activity related information of the users in soft real-time fashion. Most applications in acute, post-acute, and chronic care require strict guarantee of QoS (i.e, BER ¡10^{-10}). Even non-critical applications of prevention and wellness service (i.e., sports, fitness and lifestyle) require QoS support to make these applications effective.

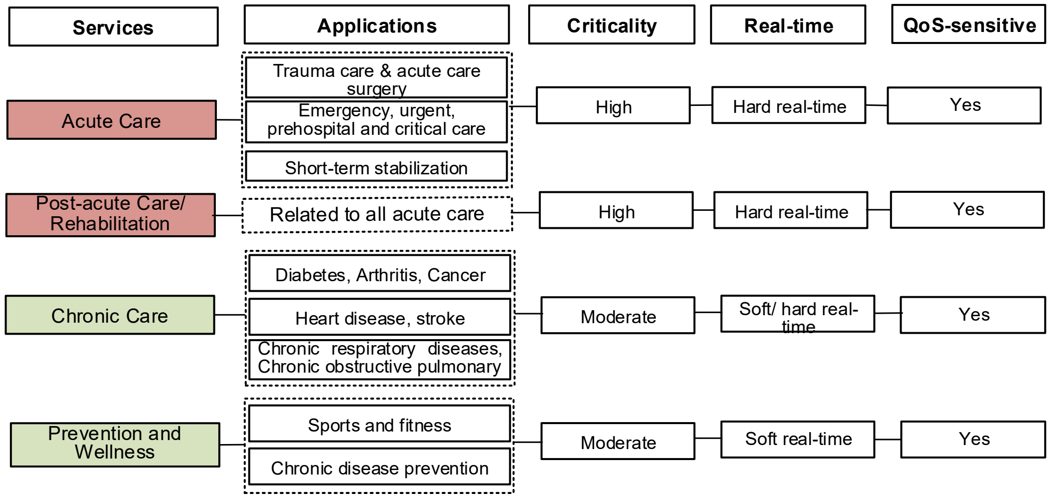


Fig. 2. Key services, and corresponding applications of BANs.

3. QOS REQUIREMENTS IN BANS

QoS is an overloaded term with different meanings and perspectives. There is a little consensus on the precise and standard definition of QoS. Different people and communities perceive and interpret QoS differently [Lai and Palaniswami 2011]. Standard definitions of QoS related terms and requirements for BANs are unavailable.

Two main stakeholders of BANs-based service or application are: (i) subject or data producers and service consumers and (ii) service providers who consume data. Generally, service or care providers (e.g., clinic or hospital with or without support a third party) offer integrated services (i.e., hardware resources- sensors, wearable devices, medical care). A BAN based on those hardware resources offers information about the patient or user of it to a service provider using sensor measurements of physical processes. For comprehensive QoS support in BANs-based service or application, it is important to address Quality of Information (QoI) that a BAN offers to service providers and consumers (e.g., provider's feedback) and quality of resources the BAN offers to its users. Quality of information is an important resource for service providers in planning, managing, delivering, and monitoring quality and safe care (Figure 1). QoI depends on data quality that refers to data that is accurate, valid, reliable, relevant, legible, complete, and available in a timely manner to decision-makers for planning and delivery of services [Pipino et al. 2002]. To provide quality data, network structure of a BAN, including its different tiers needs to be aware of quality in terms of measured sensor data (e.g., accuracy, precision), computation (e.g., timely), and communication (e.g., energy efficient, secure, and reliable communication) involved in sensor data [McGrath and Scanaill 2013; Lee et al. 2012a]. On the contrary, quality of resource services depends on a number of factors (e.g., wearability, ease-of-use, safety) related to users of those resources [Knight et al. 2002; Cherrylyn and Hee-Cheol 2013; Motti and Caine 2014]. Resource quality plays an important role in providing data quality. For example, if a device is safe, comfortable, and easy-to-use, this will motivate chronic disease patients, who are generally reluctant to wear otherwise.

Diverse applications of BANs have diverse QoS requirements. It is hard to identify these requirements individually and exhaustively. Moreover, it is unlikely that a "one-size-fits-all' QoS support solution will satisfy every application's requirements. Traditional application and network or communication perspectives of QoS require-

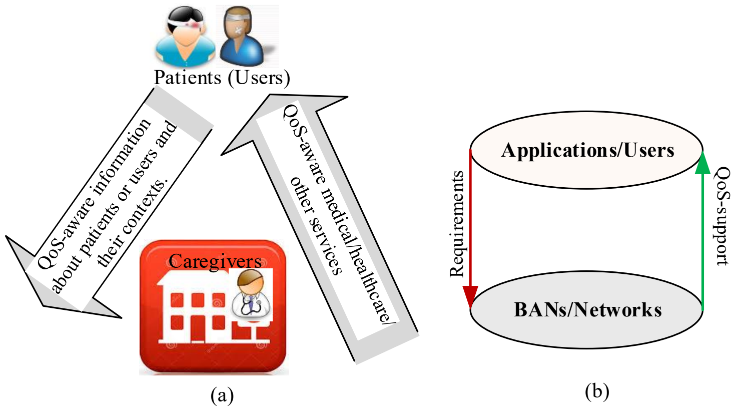


Fig. 3. (a) Users & Caregivers' relation (QoS), (b) A simple QoS model [Masud 2013].

ments (Figure 3 (b)) are useful in BANs. Generally, QoS in application perspective refers to a quality that is perceived by a user or an application. Generally, applications/users are unaware of how their underlying networks manage their resources to provide QoS. They are only concerned with services and information that networks or systems provide. On the contrary, in network perspective, a QoS is a measure of a service quality that a network offers to an application [Ganz et al. 2003]. A network's perspective of QoS can be considered as a system perspective of QoS where the network's/system's goal is to offer QoS, maximizing the network's or system's resource utilization [Sabata et al. 1997]. Generally, an application perspective of QoS requirements follows a top-down design approach, and a network perspective of QoS requirements follows a bottom-up approach.

3.1. QoS Metrics

QoS metrics quantitatively or qualitatively present QoS requirements. Finding the appropriate and exhaustive list of QoS metrics for BANs is a challenging task as metrics can be application-specific. A number of QoS requirements (e.g., timeliness, reliability) in BANs exploit end-to-end metrics (e.g., delay, redundancy), which require contributions from all the tiers of a BAN. Few other QoS requirements (e.g., comfortability, safety) may exploit metrics that are not end-to-end and need support from only from a tier of a BAN. Unlike typical WSNs, sensors in BANs are heterogeneous in nature and purpose. This may require individual sensor level (e.g., accuracy) QoS management, especially in critical applications. The main QoS requirements for BANs and their corresponding metrics are summarized below in terms of data quality, network parameters, and human factors.

3.1.1. Data Quality.

In general, Data Quality (DQ) in an Information System (IS), including BANs, can be categorized [Abdelhak M 1996; Strong et al. 1997] as: (i) intrinsic DQ, (ii) accessibility DQ (iii) contextual DQ and (iv) representational DQ. Metrics related to each DQ category and relevant to BANs applications are presented in the following.

Accuracy: Accuracy of data refers to how closely the data correctly captures what it was designed to capture. This is related sensor's measurement accuracy [Karl 2004]. In BANs, sensor nodes should provide highly accurate data gathering and processing mechanisms to offer correct information to the caregivers/applications. Gathering sensor readings as close as possible to the point of an activity or a subject improves accuracy. The accuracy requirement of a measurement should be balanced with the importance of decisions that will be made based on the measured data and the cost and effort associated with that measurement.

Believability: The extent to which data gathered by a BAN is considered as true and credible. The data gathering process in a BAN needs to make sure that sensors used in the BAN measure believable data related the objective signal of interest. For example, a body temperature sensor should provide temperature values in the range of $30 - 45C^o$ to become believable. Devices and technologies from tier one of a BAN is responsible for this quality issue. Sensor data precision that measure the probability with which a given accuracy is achieved [Karl 2004; Darwish and Hassanien 2011] is key for data believability.

Ubiquitous Access: Caregivers or service providers, especially health and medical caregivers should be able to access patient's information, including individual sensor reading anytime and from anywhere. Restricted access to BANs resources (e.g., sensors data, patient information) could make applications of BANs inflexible, especially the remote monitoring applications. Tier 2 and 3 devices, technologies, and protocols are mainly responsible for ubiquitous access of BANs' resources.

Access Security: Data security, specifically data access security in BANs is important to restricts unauthorized access or manipulation of life critical data or information. Secure data also maintains quality of information by keeping the confidentiality, integrity, and availability of information. Devices and technologies from all the tiers of a BAN are responsible for data access security in an application [Li et al. 2010].

Completeness: All required data for an application or patient need to be collected by a BAN. Incomplete data may produce negative consequence. For example, in case of a BAN-based multi-conditional (i.e., heart disease, diabetics) chronic disease management, the BAN needs to gather measure heart rate, blood pressure, and blood sugar. Missing of one of the measurements may lead to wrong treatment because of their dependency. Devices and technologies from tier one of a BAN is responsible for this quality issue.

Data Freshness or Timeliness: Out-of-date information is irrelevant in a real-time application, and could negatively affect the system. QoS requirements can be analyzed based on real-time (RT) and non-real-time (NRT) applications. In RT applications, timeliness requirements can be categorized into: hard real-time (HRT) and soft real-time (SRT). In a system with HRT requirement, a deterministic end-to-end delay needs to be guaranteed and late delivery is intolerable [Shu and Dolmans 2008; Patel and Wang 2010]. However, in SRT systems, a probabilistic guarantee is sufficient as these can tolerate some delay. To support timeliness in RT applications, a BAN should offer deterministic or probabilistic end-to-end delay guarantee. Technologies and devices from all the tiers and protocol layers of a BAN are responsible for the delay or timeliness in that BAN.

Reliability: Reliability of data refers to the extent to which data is collected consistently over time and by different sensors. Data reliability depends on reliable sensor measurements (data) and delivery of the measured data. Spatial redundancy of sensors provides reliable sensor measurements. Reliable data delivery depends on the communication reliability of the communication channels, technologies, and protocols used in data delivery. Communication reliability can be improved by exploiting measurement redundancy or by adding error correction mechanisms [Razzaque et al. 2014]. Technologies and devices from all the tiers and protocol layers of a BAN are responsible for reliability.

Data Consistency: Data consistency is to ensure that caregivers or service providers receive up-to-date and in order data on time every time. Different applications' and caregivers' (e.g., doctor, nurse, insurer) could access a dataset, and their views of the dataset should be consistent. Internal consistency of data is known as the coherence of data. In BANs, coherency should be maintained between temporarily and spatially related sensor data. Inconsistent data may cause an ineffective even wrong treatment/care [O'Donoghue and Kennedy 2006; O'Donoghue et al. 2008; HIQA 2011].

Interpretability: Interpretability of data refers to the ease at which the user can understand the data. Any ambiguity in understanding the data by a caregiver may delay the care or treatment, or even can cause wrong treatment or care. Technologies and devices form tier three of a BAN are mainly responsible for processing and interpreting data.

3.1.2. Network Related.

Delay: To support data freshness or timeliness, all the networking protocols and devices from all the tiers need to be aware of the delay requirements of the applications running on them. The total delay in a BAN application includes measurement/sensing, computation/processing, and communication delay. Delayed data or information could be useless, even dangerous in critical applications. Erroneous channel, reliability, and energy efficiency may cause delay in a network. Trade-offs are necessary among reliability, energy efficiency, and delay.

Delay Jitter: Delay jitter is the variation in the delay or latency across a BAN. Fully reliable protocols like TCP have too much latency and jitter as these protocols require acknowledgments to verify deliveries. Delay jitter can be more damaging than delay [Park and Kenyon 1999] in critical applications of BANs. In some cases trade-off some latency for jitter by creating a receiving buffer to smooth out an incoming data stream is acceptable [Kenyon et al. 2004]. Technologies and devices from all the tiers and protocol layers of a BAN are responsible for delay jitter.

Throughput: Throughput of a link or communication channel is the rate of successful message or packet delivery over the link or communication channel. In BANs most applications are critical, and need higher throughput. Higher packet delivery ratio (PDR) offers higher throughput and lower delay. Throughput and Packet Error Rate (PER) can be used to judge communication quality, including communication reliability [Zhou et al. 2011; Patel and Wang 2010] in dynamic on body and in body communications. Technologies and devices from all the tiers and protocol layers are responsible for throughput.

Packet Error Rate(PER): PER of a communication link is the number of incorrectly received data packets divided by the total number of packets received over that link. A packet is considered as incorrect if at least one bit of it is erroneous. In harsh body and hospital environments, wireless channels/links suffer from low Signal-to-Noise-Ratio (SNR) and high PER, which may increase Packer Loss Ratio (PLR) [Zhou et al. 2011; Patel and Wang 2010]. In body and on body pathlosses are mainly responsible for low SNR and high PER. Generally, technologies, devices, and protocols from tier one and two and their physical and link layers of a BAN are responsible for PER.

Energy Efficiency: Batteries are easy to replace in on body sensors of a BAN. Moreover, many on body sensors-based applications of BANs need a lifetime upto a week [Patel and Wang 2010]. Energy efficiency can be considered as QoS metric for the on body BANs. On the contrary, it is hard to replace batteries in implanted and in body sensors. Energy efficiency is of utmost importance and is a key design concern for protocol design and development for in body BANs. Energy inefficient sensing, processing, and communication may cause frequent replacement of batteries, which is highly undesirable in implanted and in body sensors. Typically, energy efficiency is a requirement for resource-constrained devices of tier one of BANs, which depends on power consumption of sensors and sensor nodes [Ameen et al. 2008; McGrath and Scanaill 2013].

Interoperability: A BAN should work with heterogeneous devices/technologies/applications, without additional effort from an application developer. Heterogeneous components should be able to exchange data and information. Interoperability in a BAN can be viewed from network, syntactic, and semantic perspectives, each of which must be supported in a BAN. A BAN should be able to exchange information across different BANs, potentially using different communication technologies. Syntactic interoperation allows heterogeneous formats and encoding structures of exchanged information or data in BANs. Semantic interoperability provides interoperability at the highest level, allows two or more BANs or elements of a BAN to exchange information and to use the exchanged information (e.g., $bodytemperature > 100.4F/38.0C$ should be semantically same or means fever) [Brailer 2005; McIlwraith and Yang 2009; Hanson et al. 2009a; Schmitt et al. 2007; Clarke et al. 2007]. Devices, technologies, and protocols from all the tiers of a BAN should be interoperable.

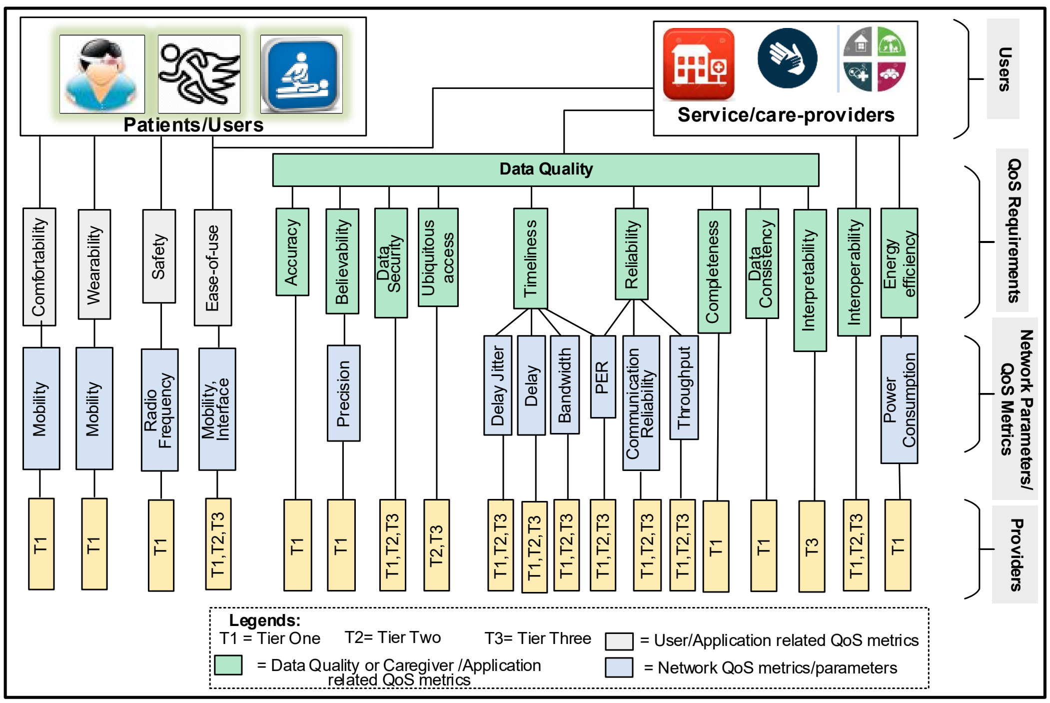


Fig. 4. QoS taxonomy in BANs

Figure 4 presents a taxonomy of QoS in BANs. This presents the key QoS requirements through their QoS metrics, their related network parameters or QoS metrics, and the contributory tier or tiers of a BAN. In every tier, these QoS requirements or metrics can be discussed in terms of their network level implementations, in particular layer-wise (e.g., Physical, Link, Network, Transport, and Application) implementations in the TCP/IP protocol stack. Table I summarizes key QoS requirements using their metrics and their contributing protocol layers. All QoS metrics mentioned in Figure 4 and in Table I are not mutually exclusive. Some of these are correlated or overlapped. For example, believability and accuracy do not represent independent (orthogonal) axes. Also, some of them are inversely related. On the other hand, energy

Table I. Summary of key QoS metrics in BANs

Metrics	Users	Providers	Network Parameters	Network Layers
Accuracy	Service providers	Tier One and Three	None	Physical
Believability	Service providers	Tier One	None	Physical
Ubiquitous Access	Service providers	Tier Two and Three	Mobility, Bandwidth, Storage	Physical, Link, and Application
Data security	Service providers, Patients	All	Security	All
Completeness	Service providers	Tier One	None	Physical
Timeliness	Service providers, Patients	All	Latency, Bandwidth, Storage	All
Data Consistency	Service providers, Patients	Tier One and Three	Reliability, Storage	Application, Transport, and Physical
Reliability	Service providers, Patients	All	Reliability	All
Interpretability	Service providers	Tier Three	None	Application
Delay	Service providers	All	Sensing, processing and communication delay	All
Delay Jitter	Service providers	All	Jitter	All
Throughput	Service providers	All	Throughput	All
PER	Service providers	Tier One and Two	PER, BER	Physical and Link
Energy Efficiency	Service providers	Tier One and Three	Power consumption	All
Comfortability	Patients/Wearers	Tier One	Mobility	Physical
Wearability	Patients/Wearers	Tier One	Mobility	Physical
Ease-of-use	Wearers, Service providers	All	Mobility, Interface	Physical and Application
Safety	Patients/Wearers	Tier One	Radio Frequency	Physical

efficiency aims to minimize redundancy in measurements whereas reliability needs to maximize redundancy [Sabata et al. 1997].

3.2. Resource Quality

Comfortability: Wearable devices, including sensors should be comfortable as user may need to wear many of these for a long time. Users should not feel pain and even presence of a sensor device after sometime wearing the device [Cho 2009]. Comfortable devices should fit users, enabling normal movements without constraints (e.g., physical or psychological). Flexible materials [Knight et al. 2005], smaller form factors, and convenient sensor locations on the body increase the users' comfortability [Van Hoof and Penders 2013; Hanson et al. 2009a; Tharion et al. 2007].

Wearability: Wearable sensors, sensor nodes, and other devices in BANs should be light and compact, unobtrusive, ergonomic, easy to put on, few, and even stylish. A trade-off between a sensor's wearability and its battery's capacity is necessary because of their conflict. Advancement in miniaturization of integrated circuits and batteries will improve body sensors' and sensor nodes' wearability [Hanson et al. 2009a; Siewiorek et al. 2008; Gemperle et al. 1998].

Ease-of-use: Use of BANs or BANs applications should require little physical and mental effort [Bergmann and McGregor 2011]. Service providers and consumers (e.g., patients, athlete) want BANs to be simple-to-use. Easy to learn and operate technology makes users more comfortable and confident in using it. A straightforward, simple, and intuitive interface [Siewiorek et al. 2008] improves the usability of a device or system, increasing engagement levels of users. Both input and output interfaces in a BAN should be easy-to-use [Cho 2009].

Safety: Technologies, devices, and protocols for BANs need to be safe for users. Safety in BANs has many perspectives, including operational (e.g., fault-tolerant), interaction (e.g., thermal and radiation safety), electrical, mechanical, software, and biocompatibility [Hanson et al. 2009a; Li et al. 2010]. Also, wearable and implanted sensors need to be unobtrusive to become safe for users. Lack of safety in one of these aspects could make a BAN dangerous or hazardous for the users. For instance, unsafe and uncontrolled thermal effects of a BAN could cause thermal damage to some organs because of temperature rise even with modest heating [Hirata et al. 2000; Tang et al. 2005]. Tier-one devices, technologies, and protocols are mainly responsible for safety in BANs, which need to comply with the SAR (Specific Absorption Rate) and HIPPA (Health Insurance Portability and Accountability Act) requirements.

4. OVERVIEW OF EXISTING WORK

QoS in BANs is a very active research area. Many QoS-related proposals on BANs have been published, especially in the recent years. These proposals diverse in their approaches and implementations and address different quality issues in BANs. This survey groups these works according to the addressed or implemented BAN's tier. Proposals within a tier are classified based on the considered or implemented protocol layers (e.g., MAC, Network). Generally, communication between personal servers (tier 2) and level 3 devices use cellular (3G/4G) technology or wireless LAN, which are sufficiently matured technologies and can support QoS [Kang et al. 2015]. Moreover, a few BANs-specific research works are available on these technologies. This survey reviews the existing proposals on tier one, tier three, and their interactions with users (e.g., doctors, nurses, hospitals) of BANs.

4.1. Overview of work on Tier one of BANs

The existing QoS-related proposals on tier one are discussed according to the protocol layers: Physical/Sensors, Data Link, Network, Transport, and Application.

4.1.1. Physical Layer (PHY). Most data quality, including accuracy, believability/precision, completeness, and data consistency, depend on the physical layer's devices (e.g., sensors and sensor motes), technologies, and protocols of a BAN. Sensing technologies of sensors, size, shape, radio technologies, flexibility, etc. of sensors and sensor motes are important for quality of data and resources [Patel et al. 2012a].

Sensor and Sensor Motes: A signal of interest can be measured using different forms (e.g., contact or non-contact forms of measurement) of measurements and types of sensors (e.g., temperature can be measured electro-mechanical, resistive, and electronic sensors), which offer different levels of accuracy, believability/precision, data consistency, ease-of-use, comfortability, safety, and wearability. Cost of sensors could be an issue as expensive sensors, typically, have more sophisticated features and offer better performance. Sensors in BANs/WBANs can measure body signals in three ways: (i) contact (mostly wearable), (ii) non-contact (also considered as ambient sensors), and (iii) sample removal (e.g., glucose levels in blood) [McGrath and Scanaill 2013; Patel et al. 2012a]. This survey concentrates on the first two types as they are directly related to BANs/WBANs. Contact sensors offer better accuracy, believability/precision, and data consistency than non-contact counterparts, but suffers in comfortability and biocompatibility. For example, sensors attached to human skin can cause irritation if left in contact for long time. On the contrary, textile integrated sensors [Peiris 2013] are comfortable to wear, but these may offer in accuracy, believability/precision, and data consistency due to poor contact with signal of interests. Generally, implanted sensors need to offer higher accuracy, believability/precision, and data consistency and biocompatibility because of their critical uses. On the other hand, contact sensors' and actuators' size, form factor, and physical compatibility to human tissues are crucial. These are not that critical for non-contact sensors as they do not require direct contact with human body. Non-contact sensors are commonly used in ambient sensing, for example, track daily activities and behaviors of patients in their own homes [McGrath and Scanaill 2013; Patel et al. 2012a]. The BANs' QoS-related existing works on sensors and sensor motes are highlighted in the following.

The medical and healthcare industries are one of the major drivers for sensor and sensor mote miniaturization (e.g., micro-scale). Most DQ, including high reliability as most medical and healthcare applications (in body) need extremely small and accurate sensors with high precision. Moreover, small and portable medical and healthcare equipment provide quicker and easier mobility of caregivers and equipment because of their lesser space requirement. The miniaturization of sensors and sensor motes play a key role in the development of wearable systems. Researchers in academia and industries are working in parallel on miniaturization and accuracy of wearable sensors and sensor motes [Hadjidj et al. 2012; Patel et al. 2012b; Crosby et al. 2012; Buckley et al. 2012; HERZOG 2013; Honeywell 2014; Peiris 2013]. The wearable photoplethysmograph ring (WPPGR) biomedical sensor developed in [Yang and Rhee 2000] improves wearability. The WPPGR sensor was improved in terms of noise resistance and energy efficiency [Asada et al. 2003]. The continuous wearability of the WPPGR sensor offers continuous monitoring of cardiopulmonary vital signs. In an EU project named AMON [Anliker 2004] researchers developed a wrist-worn device capable of monitoring blood pressure, skin temperature, blood oxygen saturation, and ECG. The AMON's device was developed to monitor high risk patients with cardio-respiratory problems. Researchers have designed and developed an ingenious monitoring system [Corbishley and Rodriguez-Villegas 2008] to measure respiratory rate using a miniaturized wearable acoustic sensor (i.e., microphone). The Human++ project [Penders et al. 2008] has developed a wireless ECG patch sensor. Multifunction sensors can support miniaturization, several assembly, and manufacturing benefits, including simplified device design, manufacturing, and installation, improved patient comfort, and safety. However, these integrated sensors' fewer parts and fewer connection points could also be potential sources of failure [HERZOG 2013]. Sensors integrated with intelligence could also support product miniaturization. Manufacturers can further reduce form factors of sensors by replacing external resistors, capacitors, and amplifiers by digital interfaces to the sensors [Honeywell 2015b]. Researchers have developed a miniature, flexible, and noninvasive electronic patch [Haahr et al. 2012], which has the potential to improve wearability and comfortability.

Industries are also developing miniature and high accuracy sensors [Brookhuis 2014; melexis 2008; Devices 2009; Honeywell 2015a]. Recently, Twente University [Brookhuis 2014] has revealed a prototype of the world's smallest hand-force sensor. The sensor is smaller than a fingertip, can be used in gloves and prosthetic devices to measure the forces exerted by hand. Another example of a miniature sensor for common medical apps is the ultra-small, intelligent non-contact IR thermometer from the Melexis Technologies [melexis 2008]. Miniature 3-axis accelerometer with high accuracy are also available for sports and healthcare applications [Devices 2009].

Ensuring interoperability, especially multi-vendor interoperability is key for enabling BANs applications, including the personal telehealth applications, because of existing isolated and diverse solutions. A set of ISO/IEEE 11073 Personal Health Device (PHD) Communication standards [Schmitt et al. 2007; Clarke et al. 2007] has been developed to close this gap regarding application and data layer interoperability in the personal health domain. Telehealth industries are adopting ISO/IEEE 11073 standards to enable end-to-end system interoperability [Int 2016].

An ideal wearable computer or BAN would be as convenient, durable, and as comfortable to wear as clothing. Considering these issues and the recent advances in textile-based electronics, use of systems on textiles (SoTs) are gaining a great deal of interest among researchers in the field of wearable technology [Yoo 2013; Peiris 2013; Pantelopoulos and Bourbakis 2010; Patel et al. 2012a; McGrath and Scanaill 2013]. A self-configurable wearable body sensor network with wireless power connection is developed for continuous monitoring of patient's ECG [Jerald Yoo and Yoo 2010]. Researchers in [Yan et al. 2011] have developed a plaster (poultice like) sensor-based wearable SoC for cardiac patients. The SoC is a low power system that performs thoracic impedance variance (TIV) and ECG monitoring. Patch like systems rely on fabric circuit board and wearability. A lightweight and coin-sized fabric patch-based BAN is useful for sleep-monitoring [Lee et al. 2012b]. Along with textile-based sensors, biochemical sensors (e.g., blood glucose level sensors) are gaining a lot of interest from wearable technology researchers. The BIOTEX project [Coyle et al. 2010] has developed an array of bio-chemical sensors. These textile integrated bio-chemical and comfortable sensors can monitor body fluid. Similarly, the ProeTEX project [Curone et al. 2010] has developed a wearable sensorized garment for firefighters. This garment includes sensors to measure CO_2, movement, environmental and body temperature, position, blood oxygen saturation, heart rate, and respiration rate. These non-contact sensors may offer resource quality, but suffers in DQ.

Sensors, especially in body sensors should be flexible enough to ensure that the sensors are positioned as close to a patient or signal of interest (e.g., pharmaceuticals, blood or water) as possible for accurate, precise/believable and consistent measurements [Mathas 2015]. Recent studies on flexible mechanical and electrical sensing devices have shown a great potential in numerous applications including healthcare. E-skins are wearable or skin-attachable electronic devices for motion detection or a diagnostic tool to monitor body signals. Polymer-based support layers of e-skins offer biocompatibility and comfortability. Moreover, e-skins sensors include several innovative features, including transparency [Lipomi et al. 2011], self-healing capabilities [Tee et al. 2012], and energy harvesting. Generally, e-skin can sense the spatiotemporal distribution of an external stimulus with a soft substrate. High flexibility and high sensitivity requirements are the main driving force of various research directions in design and fabrication e-skins. An early version of an e-skin relied on flexible organic transistors [Someya et al. 2004]. Nanowire-based artificial e-skin offers flexibility exploiting rubber as a base substrate and sensing element [Takei et al. 2010]. Along with the advances in e-skins, many innovative approaches have been proposed for skin-attachable devices for human motions detection and in vitro diagnostics on skin. Recently bioinspired approaches are used for skin-attachable sensors through the mimicking of unique structural features of the gecko lizard. The hairy structure-based dry adhesive patch offers comfortability because of its less surface contamination, more ventilation of air, moisture, and skin residues [Kwak et al. 2011; Bae et al. 2013]. The single walled carbon nanotubes (SWCNTs) based highly stretchable human motion detector or sensor offers flexibility [Yamada et al. 2011]. A flexible and skin-attachable strain-gauge sensor based on nano-interlocking mechanism [Pang et al. 2012] supports simple but robust sensing platform. The epidermal electronic systems (EES) can read various physiological signals [Kim et al. 2011]. This ultra-thin tattoo-like system can maintain necessary structure on the skin even under an extremely bumpy state and offer better DQ.

Table II. Key properties of popular sensor motes used in BANs research

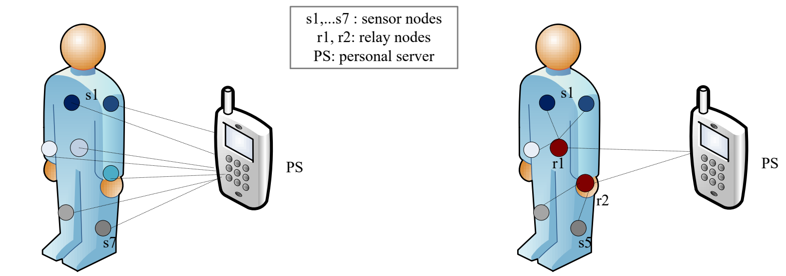
Mote	Size(mm)	Weight(g)	1bit Tx / Rx cost(μJ)	Interoperability
Mica2 [Memsic 2016]	$58 \times 32 \times 7$	63.05	2.11/.78	No
TelosB [Memsic 2016]	$63 \times 31 \times 6$	63.82	.237/.261	No
BSN v3 [BSN 2014]	19×30	NA	.237/.261	No
Imote2 [Crossbow(Imote2) 2011]	30×40	63	.237/.261	No
SHIMMER [Ko et al. 2010]	$44.5 \times 20 \times 13$	10.36	.237/.261	IEEE802.15.4 and Bluetooth

Along with the researchers' effort, sensor industries are producing flexible, miniature, and multifunctional sensors. These sensors are offering new health and medical care systems such as surgical devices [HERZOG 2013; Chansin 2015]. Flexible sensor packaging styles, including manifold-mount, and cable assembly options offer greater flexibility for the designers to position the sensor on the printed circuit board (PCB). This simplifies device design eliminating tubing and related connections, making a smaller medical device. Flexible mounting options [HERZOG 2013; Pang et al. 2013] ensure that the sensor can be positioned exactly where it needs to be - for accurate, precise, consistent, and complete measurement. Honeywell's TruStability HSC/SSC [Honeywell 2014] is an example of this type sensor. These sensors also offer wearability and cofortability [Chansin 2015].

Accuracy and consistency of a sensor measurement significantly depend on the technology of the sensor. For example, electrochemical sensors offer higher accuracy and better consistency compared to semiconductor sensors. With standalone sensors, guaranteeing the accurate measurement of a representative sample is a difficult task. In cooperative sensing, it is possible to optimize the performance of an individual sensor, in particular, accuracy of the measurement exploiting data from another sensor (e.g., temperature drift compensation) [Hunter and Liu 2010; McGrath and Scanaill 2013]. This also improves the believability of sensor data.

In addition to SoCs, SoTs, different sensor motes are used in various BAN-based research works [Penders et al. 2008; Johnson et al. 2009; Pantelopoulos and Bourbakis 2010; Nabar et al. 2010; Crosby et al. 2012]. Table II summarizes the key properties of few popular sensor motes used in BANs research. The table listed the Mica2, TelosB [Memsic 2016], BSN v3 [BSN 2014], Imote2 [Crossbow(Imote2) 2011] and SHIMMER [Ko et al. 2010] in terms of size, weight, battery (related to comfortability), 1bit transmission(Tx)/reception (Rx) cost (related to energy efficiency), and interoperability. In terms of weight and size SHIMMER [Ko et al. 2010] outperforms others (except BSN v3, as detail information on size and weight is not available). Per bit transmission and reception cost is higher for Mica2 mote compared to the others. SHIMMER [Ko et al. 2010] is the only mote that support communication level interoperability (limited scale) by supporting IEEE802.15.4 and Bluetooth. The rest of the motes support only IEEE802.15.4. In many applications, wearable sensor motes/nodes are used for long time, which can heat up the processor or other components of the motes. Thermal safety of sensors and sensor motes is important to avoid consequences of heating on human tissue or organs. As evaluated in [Nabar et al. 2010], most of the listed motes are thermally safe.

Communication Technologies: The communication architecture between the tier one and PS of a BAN can be flat Figure 5(a) and hierarchical Figure 5(b) [Ullah et al. 2010a]. In a flat architecture sensors directly send their measured data to the PS, whereas in a hierarchical architecture sensors send their measured data to a relay or gateway node that sends them to the PS. In QoS perspective, a hierarchical architecture is preferable compared to a flat one because of the hierarchical architec-



(a) Flat architecture of BAN

(b) Hierarchical architecture of BAN

Fig. 5. BAN's Architecture.

Table III. Key properties of popular sensor motes used in BANs research

Properties	802.15.1	802.15.4	IrDa	MICS	802.11g	802.15.6
Frequency Band	ISM	ISM	Infrared	402-405MHz	ISM	Regulatory and/or medical authorities approved
Range (m)	10-100	10-75	1	2	200	2-5
Data Rate	1-3Mbps	20/40/250 Kbps	16Mbps	.5Mbps	54Mbps	Kbps-10Mbps
Power Consumption (mW)	2.5-100	25-35	-	.025	1000	.01 - 40
Safety	None	None	NA	Meet SAR requirements	None	Meet SAR and HIPPA requirements
QoS-awareness	No	No	No	No	No	Yes

ture's performance (e.g., delay, PDR, energy consumption, and network lifetime) in BANs [Shankar et al. 2001; Braem et al. 2007; Natarajan et al. 2007b]. In hierarchical or multi-hop BANs communication from sensor nodes to a relay node or intra-BAN communications can be handled either by a wired or by wireless link. A wired and favorable approach for this can be e-textile [Yoo 2013; Peiris 2013; Pantelopoulos and Bourbakis 2010; Patel et al. 2012a; McGrath and Scanaill 2013]. Wireless communication is a very popular option, but it may suffer due to the impact of shape, size, movement, and other issues related to wearers' body on signal propagation [Latré et al. 2011]. Communication between sensors or relay node and the PS can be wired or wireless. However, in wired communication users' mobility and daily activities are limited [Townsend et al. 2005; Pantelopoulos and Bourbakis 2010]. Most existing research proposals address safety of wireless communication.

IEEE 802.11 (WLAN), IEEE 802.15 (WPAN), IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Zigbee), etc. [Patel and Wang 2010; Latré et al. 2011; Pantelopoulos and Bourbakis 2010; Patel et al. 2012a; McGrath and Scanaill 2013] are the widely used wireless communication standards in BANs. These technologies offer most basic requirements of BANs (e.g., health and medical care applications), but they suffer in issues like QoS-awareness, including safety (human), ultra-low power requirements, etc. These issues motivated the researchers in this field to develop a new standard for BAN named IEEE 802.15.6 (BAN) [Wang and Wang 2011]. Infrared (IrDA), the medical implant communication service (MICS), and ultra wideband (UWB) are few of the alternative technologies for short-range intra-BAN communication. Table III summarizes these technologies in terms of power consumption, data rate, range, frequency, safety, and QoS-awareness. IEEE 802.11g, IEEE 802.15.1 (Bluetooth), and IEEE 802.15.4

(Zigbee) use widely available, but crowded ISM (Industrial, Scientific, and Medical) band which may increase PER because of potential collisions. IEEE 802.15.6. supports regulated or medical authorities approved or both frequency bands. This supports three physical layers namely Narrowband (NB), Ultra Wide Band (UWB), and Human Body Communication (HBC) and the use of these layers depends on the application requirements. Unlike the ISM band, any band used in IEEE 802.15.6. needs to comply with the SAR (Specific Absorption Rate) and HIPPA (Health Insurance Portability and Accountability Act) requirements. The IrDA uses infrared and MICS uses 402-405MHz, which are generally safe. Typically, medical applications need 2-5 meter communication range (IEEE 802.15.6.), which is shorter than the typical range of IEEE 802.15.4 (Zigbee). Even with many benefits IEEE 802.15.4 (Zigbee) suffers in BANs due to low data rate, lack QoS-awareness, coexistence with ISM band technologies, and on body use only. On the other hand, Bluetooth suffers due to lack of compatibility, scalability, and QoS-awareness, coexistence with ISM band technologies, and on body use only. IrDA suffers in BAN's medical applications due to line-of-sight communication requirement. Despite of favorable characteristics (e.g., low power, safety), MICS, especially used in implanted or in body sensors suffers due to commercially unavailable MICS solutions and in body use only [Pantelopoulos and Bourbakis 2010; Fang et al. 2011]. The wireless communication technologies mentioned in Table III are symmetric (as downlink and uplink data rate are same). Typically, in BANs communications from sensor nodes to PS (uplink) need a higher data rate than those from PS to sensor nodes (downlink) as the uplink carries the sensed information (data), while the downlink may carry configuration instructions or similar, low-bandwidth information. Most existing wireless communication technologies in BANs can be energy in-efficient because of this asymmetric requirement. Use of separate RF strategies for uplink and downlink can be useful [Calhoun et al. 2012] as this may optimize the asymmetric energy consumption and data rates in BANs.

Existing Wearable Devices: Many activity trackers and smart watches with the promise of healthier living have hit store shelves over the last couple of years [Specout 2015]. These devices (e.g., Apple's smart watch, Microsoft's band, Jawbone's wrist band, Fitbit's fitness band) along with the supporting software, can gather information like steps, sleep, heart rate, sun exposure, and calories. Most of these wearable tracking devices are attractive, easy-to-use, accessible, and comfortable. However, most of these devices lack health and medical care grade DQ, including accuracy, consistency, data security, and believability [Metz 2015; Case et al. 2015]. Many wearable device makers believe that users' engagement is more important than accuracy [Comstock 2015].

4.1.2. Data Link Layer. Generally, a data link layer in a protocol stack provides services, including framing, Media Access Control (MAC), error detection and recovery. MAC and error detection and correction mechanisms are critical for BANs [Latré et al. 2011] because of in and on body path losses, wireless network's dynamic channel and environmental conditions (e.g., hospital). It is impossible to support QoS in the upper layers (i.e., network, transport) of a BAN without the support of MAC protocol as it offers medium sharing and reliable communication. This layer also responsible for, such as energy efficiency by duty cycling and dynamic environmental conditions by error correction mechanism [Razzaque et al. 2014] or transmission power control.

In BANs, MAC protocol needs to be scalable, reliable, energy efficient, and fast responsive. Coordinated coexistence of many collocated BANs in crowded places, such as hospital elevators and wards needs a robust MAC protocol. Efficient duty cycling methods are necessary to support energy efficiency without compromising other QoS metrics. The MAC protocol and error recovery mechanism need to be adaptive to cope

Table IV. Existing BAN-specific MAC Protocols and QoS-awareness in BANs

MAC Protocol	Key Features	Considered QoS	Remarks
BSN-MAC [Li and Tan 2005]	IEEE 802.15.4 and scheduled-contention based	Timeliness, energy efficiency	Rely on IEEE 802.15.4
Omeni [Omeni et al. 2007]	TDMA based, reduce collision and idle listening	Energy efficiency	Not scalable
Battery-aware TDMA [Su and Zhang 2009]	TDMA based, considers battery discharge dynamics	Energy efficiency	High delay and packet drop, no in-body support, and complex
Energy-efficient MAC [Marinkovic et al. 2009]	TDMA based, multiple PHYs support	MAC compatibility, energy efficiency	Considered static BAN, lacks wake up mechanism for low duty cycle nodes
BodyMAC [Fang and Dutkiewicz 2009]	Scheduled-contention based, flexible bandwidth allocation	Timeliness, energy efficiency	Not suitable for in-body, uses unreliable CSMA/CA
HMAC [Li and Tan 2010]	TDMA based, exploit heartbeat rhythm for synchronization	Energy efficiency	Do not support sporadic events, synchronization may suffers
DQBAN [Otal et al. 2009]	QoS-aware urgency based MAC, fuzzy rule based scheduling algorithm	Reliability, energy efficiency	Complex algorithm, no service differentiation, not adaptive to channel conditions
IEEE 802.15.6 [Wang and Wang 2011]	BAN dedicated, support different PHYs, QoS-aware	Most QoS	Complex
U-MAC [Ali et al. 2010]	QoS-aware urgency based MAC, exploit sensors' priority	Timeliness, energy efficiency	Not adaptive to channel conditions, low priority sensors suffer
MEB-MAC [Huq et al. 2012]	Priority-based and traffic adaptive MAC for BAN (Emergency traffic)	Reliability, timeliness	Considered only emergency traffic and reliability is not adaptive to channel conditions
Self-organizing MAC [Maman et al. 2013]	Self-organizing, adaptive, and flexible MAC	Energy efficiency	Trade-off between energy efficiency and other QoS (e.g., reliability)
Priority MAC [Bradai et al. 2013]	QoS-aware priority based MAC for BAN	Reliability, energy efficiency	Reliability is not adaptive to channel conditions
PLAMAC [Anjum et al. 2013]	Traffic priority and load-adaptive MAC	Packet-level priority, reliability	Reliability is not adaptive to channel conditions
CLNC-MAC [Kartsakli et al. 2014]	Cloud-assisted random linear network coding-based MAC	Throughput, reliability	Complexity and delay
Energy efficient MAC [Lin et al. 2014]	TDMA based MAC for multi-Hop swallowable BAN	Energy efficiency	Limited to in body BAN and considered only energy efficiency
WuR-based MAC [Ramachandran et al. 2015]	CSMA and TDMA based MAC, uses wake-up radio	Energy efficiency, timeliness, reliability	Only for in body BAN, reliability is not adaptive
HEH-BMAC [Ibarra et al. 2013; 2015]	Harvests energy from human activities, polling, and probabilistic contention based MAC	Energy efficiency	Not QoS-aware

Table V. Existing BAN-specific MAC Protocols: a quanitive evaluation

MAC Protocol	PDR	Energy efficiency (microJ/bit)	Delay (sec)
BSN-MAC [Li and Tan 2005]	NA	2.15-17.5	NA
Battery-aware TDMA [Su and Zhang 2009]	.97-.99	2-3.5 times efficient than TDMA	.1-3.5
Energy-efficient MAC [Marinkovic et al. 2009]	NA	1.1-2	NA
BodyMAC [Fang and Dutkiewicz 2009]	NA	.73	.014 -.022
HMAC [Li and Tan 2010]	NA	.55	NA
DQBAN [Otal et al. 2009]	.91-.95	.15-.65	.02-.1
MEB-MAC [Huq et al. 2012]	NA	NA	1.6
PLAMAC [Anjum et al. 2013]	NA	NA	.4-.5
CLNC-MAC [Kartsakli et al. 2014]	1.0	1.65 time efficient than IEEE 802.15.6 MAC	NA
Energy efficient MAC [Lin et al. 2014]	1.0	1.6 time efficient than IEEE 802.15.6 MAC	NA
WuR-based MAC [Ramachandran et al. 2015]	.7-.97	7-17.5	.1-2.5

with dynamic network topology and density changes induced by nodes moving in and out of range due to body movements [Patel and Wang 2010].

Many BAN-specific MAC protocols have been published [Ullah et al. 2010b; Latré et al. 2011; Ullah et al. 2012; Javaid et al. 2013b]. Moreover, many researchers have considered WSNs' MAC protocols for BANs because of their commonality (e.g., a WBAN is a special kind of WSN) [Yigitel et al. 2011a]. These protocols can be grouped into contention-based and schedule-based MAC protocols. Generally, schedule-based protocols such as Time Division Multiple Access (TDMA) protocols are energy efficient and fast responsive compared to contention-based MAC protocols (e.g., Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)). However, schedule-based protocol suffers due to scalability and synchronization requirements. Table IV summarizes most existing BAN-specific MAC protocols in terms their QoS support, and Table V presents a quantitative evaluation of number of these protocols.

Most existing MAC protocols support (Table IV) one ([Omeni et al. 2007; Su and Zhang 2009; Li and Tan 2010; Maman et al. 2013]) or two ([Li and Tan 2005; Fang and Dutkiewicz 2009; Ali et al. 2010; Ramachandran et al. 2015]) QoS requirements for BAN applications. The majority of the existing MAC protocols support energy efficiency and only a few of them support other QoS metrics, including reliability, timeliness. For instance, DQBAN [Otal et al. 2009], Priority MAC [Bradai et al. 2013], MEB-MAC [Huq et al. 2012], Wake-up-Radio- (WuR)-based MAC [Ramachandran et al. 2015] work on reliability (to certain extent), BodyMAC [Fang and Dutkiewicz 2009], U-MAC [Ali et al. 2010], MEB-MAC [Huq et al. 2012], and WuR-base MAC [Ramachandran et al. 2015] address timeliness. Most existing protocols support energy efficiency, but do not satisfy other MAC requirements for BAN/WBAN applications. The LPL (Low Power Listening) and schedule-contention mechanisms do not support unpredicted sporadic events and low duty cycle nodes. The TDMA-based mechanisms support these, and most of the existing MAC protocols for BAN are based on TDMA. WuR-based MAC [Ramachandran et al. 2015] and IEEE 802.15.6 [Wang and Wang 2011] support three or more QoS requirements of BAN applications. WuR-based MAC supports timeliness, energy efficiency, and reliability, but reliability is not adaptive to dynamic channel conditions. 802.15.4 can provide most QoS requirements for BAN applications, but it is not scalable in terms of power consumption and suitable for a limited number of BAN applications [Golmie et al. 2005; Cavalcanti et al. 2007]. On the other hand, BAN-specific and QoS-awre IEEE 802.15.6 MAC is complex, but supports all BAN applications and PHYs. Researchers are working on the standardization of BANs, including the development of a unified MAC protocol.

Table V presents a quantitative evaluation of eleven MAC protocols from the Table IV in terms of PDR, energy efficiency and packet delivery delay. As shown in the table, not all of them support and/or evaluated against these QoS metrics. Only the Battery-aware TDMA, DQBAN and WuR-based MAC [Su and Zhang 2009; Otal et al. 2009; Ramachandran et al. 2015] are evaluated against all three metrics. The DQBAN is the best performing protocol in the evaluated set of protocols.

Along with a MAC protocol, an error recovery mechanism in a data link layer is useful in improving reliability, energy efficiency, and timeliness [Yigitel et al. 2011b; Thapa and Shin 2012; Marinkovic and Popovici 2009; Arrobo and Gitlin 2011; Kartsakli et al. 2014; Razzaque et al. 2014]. BANs/WBANs need QoS mechanisms which are adaptive to network channel conditions [Yigitel et al. 2011b; Thapa and Shin 2012; Razzaque et al. 2014]. However, traditional error recovery mechanisms, such as ARQ (Automatic Repeat-reQuest) and FEC (Forward Error Correction) are very difficult to make adaptive [Haghighi and Navaie 2011]. Moreover, use of complex and highly resource hungry error recovery schemes (e.g., ARQ and FEC) are undesirable in resource-constrained BANs [Xia 2008; Razzaque et al. 2014]. Network Coding (NC) based error recovery mechanisms can improve network QoS requirements, such as reliability, energy efficiency, and timeliness at low memory and hardware costs [Marinkovic and Popovici 2009]. However, the original version of NC is not adaptive to network channel conditions [Kartsakli et al. 2014; Razzaque et al. 2014]. Adaptive NC-based error recovery mechanism [Razzaque et al. 2014] offers improved QoS support in terms of reliability, energy efficiency, and timeliness. Authors in [Razzaque et al. 2014] have used adaptive NC only for links between relay nodes and PS/MS, not for links between sensors to relay nodes. Links, especially wireless links between sensors' and relay nodes' communication could be unreliable.

4.1.3. Network layer. A network layer in a BAN/WBAN is responsible for addressing, routing, and forwarding of data packets. To ensure end-to-end ontime and reliable packet delivery (e.g., patient's critical information to doctors) QoS-aware routing protocols are very important in BANs/WBANs. Development of an efficient and QoS-aware routing, including forwarding, protocol in BANs is a nontrivial task. This is because of dynamic characteristics of wireless environments on and in human body and outside body. BAN/WBAN-specific characteristics and stringent QoS requirements of BAN/WBAN applications make most existing WSN-specific routing protocols inadequate for BAN/WBAN [Akkaya and Younis 2005]. Moreover, studies [Shankar et al. 2001; Fort et al. 2006; Reusens et al. 2007; Braem et al. 2007; Natarajan et al. 2007b] showed that in QoS perspective (e.g., timeliness, reliability, energy efficiency), multi-hop communications are preferable in compare to single-hop communications. Many multi-hop routing protocols for BANs have been proposed, which are diverse in techniques and implementations. Authors in [Bangash et al. 2014a] survey these routing protocols. The survey does not include recent routing protocols, including many QoS-aware routing protocols [Bangash et al. 2014b; Ahmad et al. 2014; Ababneh et al. 2015; Bangash et al. 2015]. Table VI summarizes most existing QoS-aware routing protocols in terms of their key features and addressed QoS for BANs. Also, Table VII presents a quantitative evaluation of number of these protocols. Although, the list of protocols in these tables is not exhaustive, but sufficient to provide the state-of-the-art of QoS-aware routing protocols in BANs/WBANs.

Table VI. Summary of the existing BAN-specific QoS-aware Routing Protocols for BANs

Routing Protocol	Key Features	Addressed QoS	Remarks
RSFW [Liang and Balasingham 2007]	Priority based routing, user specific QoS support	Reliability, timeliness	Not energy efficient, moderate PDR
RL-QRP [Liang et al. 2008]	Reinforcement learning and geographic information based	Timeliness	Energy in-efficiency, unrealistic mobility model
HPR [Bag and Bassiouni 2008]	Hotspot preventing routing	Timeliness, safety	Energy in-efficient
LOCALMOR [Djenouri and Balasingham 2009]	Exploits service/data differentiation	Timeliness	Redundant communications, energy in-efficiency
DMQoS [Razzaque et al. 2011]	Exploits service/data differentiation	Reliability, timeliness	Very low throughput
QPRD [Khan et al. 2012]	Exploits service/data differentiation	Timeliness, energy efficiency	Uses unreliable CSMA/CA
QPRR [Khan et al. 2013]	Exploits service/data differentiation	Reliability, energy efficiency	Uses unreliable CSMA/CA
M-ATTEMPT [Javaid et al. 2013a]	Single/Multi-hop, minimize temperature rise, and rely on TDMA	Timeliness, safety, energy efficiency	Non-critical data suffer, single-hop communication can be unreliable
ETPA [Movassaghi et al. 2012]	Minimize thermal impact	Safety, energy efficiency	High delay
PSR [Liang et al. 2012]	Exploits predicted link quality	Reliability, security	Energy in-efficient
TMQoS [Muhammad Mostafa Monowar and Alamri 2014]	Exploits service/data differentiation, thermal-awareness	Reliability, safety	Low throughput
RE-ATTEMPT [Ahmad et al. 2014]	An improved version of M-ATTEMPT [Javaid et al. 2013a] without thermal-awareness	Reliability, energy efficiency	Non-critical data suffer, single-hop communication can be unreliable, and thermal safety
RAR [Bangash et al. 2014b]	Reliability-aware routing, use data differentiation, cross-layering	Reliability	Low throughput, reliability comes at the cost of delay and energy consumption
ARBA [Ababneh et al. 2015]	Adaptive routing and bandwidth allocation protocol for streaming data, cross-layered	Utility, load balancing, energy efficiency	Applied to unrealistic conditions only
DCR [Bangash et al. 2015]	Data-centric, thermal-awareness, adaptive pathloss consideration	Reliability, safety, energy efficiency	Unrealistic in and on body pathloss model, no real implementation

Table VII. Existing BAN-specific QoS-aware Routing Protocols:a quanitive evaluation

Routing Protocol	PDR	E2E delay (ms)
RL-QRP [Liang et al. 2008]	.95	175
LOCALMOR [Djenouri and Balasingham 2009]	.83-.95	120-215
DMQoS [Razzaque et al. 2011]	.91-.98	110-140
QPRD [Khan et al. 2012]	.95	20-30
ETPA [Movassaghi et al. 2012]	.71-.81	NA
PSR [Liang et al. 2012]	.8 -.82	NA
TMQoS [Muhammad Mostafa Monowar and Alamri 2014]	.92-.98	100-125
RAR [Bangash et al. 2014b]	.95-.99	NA
DCR [Bangash et al. 2015]	.75-.95	NA

Most of the listed existing routing protocols in BANs (Table VI) address one or two QoS requirements, including energy efficiency, timeliness, reliability, and safety (thermal). A limited number of the existing routing protocols [Javaid et al. 2013a; Muhammad Mostafa Monowar and Alamri 2014; Bangash et al. 2015] address more than two QoS requirements. Routing Service Framework (RSFW) [Liang and Balasingham 2007] addresses user specific QoS support by improving reliability and latency, but it is not energy efficient. Reinforcement Learning based Routing Protocol with QoS support (RL-QRP) [Liang et al. 2008] addresses timeliness and energy efficiency. However, RL-QRP's Random Waypoint Mobility Model (RWMM) may not be realistic all the time. Number of protocols, including Localized multi-objective routing [Djenouri and Balasingham 2009], Data-centric multiobjective QoS-aware (DMQoS) routing [Razzaque et al. 2011], QoS-aware Peering Routing Protocol for Delay Sensitive Data QPRD [Khan et al. 2012], QoS-aware Routing Protocol for Reliability Sensitive Data (QPRR) [Khan et al. 2013], and TMQoS [Muhammad Mostafa Monowar and Alamri 2014] rely on service or data differentiation. Even though they support service/data differentiation, they exploit it differently and address different QoS metrics. For example, LOCALMOR, and QPRD address energy efficiency and timeliness, QPRR addresses energy efficiency and reliability, and DMQoS support reliability and timeliness, and TMQoS addresses reliability and safety along with energy efficiency. They also suffer because of different reasons. For example, QPRD and QPRR use CSMA/CA, which is unreliable and unsuitable for BANs, and DMQoS and TMQoS provide low throughput. The Hotspot Preventing Routing algorithm (HPR) [Bag and Bassiouni 2008] applies to delay-sensitive applications of in vivo sensors. The HPR addresses timeliness and safety like M-ATTEMPT [Javaid et al. 2013a], but the HPR is energy inefficient and M-ATTEMPT's single-hop communication can be unreliable. RE-ATTEMPT [Ahmad et al. 2014] improves the reliability concern of M-ATTEMPT [Javaid et al. 2013a], but sacrifices the thermal-awareness. Like other service/data differentiation based routing protocols, non-critical data may suffer in M-ATTEMPT and RE-ATTEMPT. The Energy efficient thermal and power aware (ETPA) routing [Movassaghi et al. 2012] is an energy efficient and thermal safety-aware protocol. Energy efficiency and thermal safety-awareness may increase communication delay in ETPA. The Prediction-based Secure and Reliable routing framework (PSR) [Liang et al. 2012] is the only routing protocol in the list that addresses security along with reliability, but it can be energy inefficient. The Adaptive Routing and Bandwidth Allocation protocol (ARBA) [Ababneh et al. 2015] is a cross-layered (link and network layer) routing protocol for streaming data. The ARBA aims to improve the utility, load balancing, and energy efficiency in BANs, but limited to ideal network conditions only. The Reliability-Aware Routing (RAR) [Bangash et al. 2014b] exploits data differentiation to offer reliability for critical data in BANs. However, high priority data may result in lower overall throughput, higher delay and energy consumption for low priority data. The Data-Centric Routing (DCR) [Bangash et al. 2015] protocol considers thermal-awareness and an adaptive pathloss model to offer reliability, safety, and energy efficiency for in body BANs. The unrealistic in and on body pathloss model is a concern for the DCR.

Table VII presents a quantitative evaluation of a set of protocols from the Table VI in terms of PDR, and end-to-end (E2E) packet delivery delay. As shown in the table, not all of them support and/or evaluated against these QoS metrics, especially E2E delay. Most of the listed protocols show reliable packet delivery with 95% success rate.

Although, the presented routing protocols in BANs address one or more QoS metrics (requirements), in most cases values for these metrics are relative, which may not be sufficient for real-life applications of BANs. These routing algorithms are unaware of real on and in body path losses. Also, all the listed protocols except the (PSR) [Liang et al. 2012] do not consider security and privacy.

Table VIII. Summary of the existing QoS-aware Transport Protocols for BANs

Transport Protocol	Key Features	Addressed QoS	Remarks
CODA [Wan et al. 2011]	Congestion control, receiver-based congestion detection	Energy efficiency, throughput	Reliability and latency could be an issue
PHTCCP [Monowar et al. 2008]	Cross-layered congestion control	Higher throughput for critical traffic	Non-critical data suffers
PCCP [Wang et al. 2006a]	Cross-layered and priority-based congestion control	Energy efficiency	Low-priority traffic suffers
GARUDA [Park et al. 2008]	Reliable transport sink to sensor node	Reliability	Reliability limited to PS to sensors only
PSFQ [yih Wan et al. 2005]	Reliable transport sink to sensor node	Reliability	Limited congestion control
TRCCIT [Shaikh et al. 2010]	Congestion control, upstream reliability	Reliability, energy efficiency	Reliability limited to sensors to PS only
RT^2 [Gungor et al. 2008]	Congestion control, upstream reliability, cross-layered	Reliability, energy efficiency, timeliness	Reliability limited to sensors to PS only
ART [Tezcan and Wang 2007]	Congestion control, up and downstream reliability	Reliability, energy efficiency	Remaining energy-based non-core node selection many not be suitable in BANs
ESRT [Akan and Akyildiz 2005]	Congestion control and reliable transport mechanism	Reliability, throughput	Only upstream reliability, no loss recovery
STCP [Iyer et al. 2005]	Sink/PS controlled congestion control and reliable transport mechanism	Reliability, throughput	Only upstream reliability
LACAS [Misra et al. 2009]	Learning automata (LA)-based congestion control protocol for sensor nodes in BANs	Throughput	Node-level only, complex
CCC [Hu et al. 2009]	Uses compressive signal processing	Throughput	Not scalable, recovery is difficult in unreliable communications
QCC [Farzaneh and Yaghmaee 2011; Yaghmaee et al. 2013]	Queue-based congestion control for priority traffic for BANs	Higher throughput and timeliness for critical traffic	Non-critical data suffers
HOCA [Rezaee et al. 2014]	Active queue-based congestion control for priority traffic for BANs	Higher throughput and timeliness for critical traffic, energy efficiency	Non-critical data suffers

4.1.4. Transport layer. Transport protocol is essential for the Internet or external network connected BANs/WBANs. A transport layer protocol in tier one of a BAN needs to offer reliable packet delivery from the sensor nodes to the PS and from the PS to the sensor node in case of specific sensor queries or emergency sensor data requests. Transport protocol also offers congestion control service in a network. An efficient congestion control increases the packet delivery ratio (throughput) and network lifetime of a BAN. Conventional protocols, such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are too expensive (in terms of energy consumption and delay) and complex for resource-constrained BANs. TCPs 3-way handshake process and its end-to-end ACK communication would result in higher delay and buffer storage demands at sensor node level. On the contrary, connectionless UDP does not provide reliability and drops packets with no scope of recovery. This is a serious concern in medical and healthcare applications of BANs [Wang et al. 2006b; Hughes et al. 2012].

Energy efficient and QoS-aware transport protocols should consider the diversity of applications, traffic characteristics, and resource limitations of sensor nodes. QoS metrics (requirements) such as throughput, latency, energy efficiency, and fairness are useful in studying the QoS support of the existing transport protocols. Most existing transport protocols discussed in the literature are WSNs-centric [Wang et al. 2006b; Rathnayaka and Potdar 2013; Hughes et al. 2012; Filipe et al. 2015b]. A number of BANs-specific protocols [Misra et al. 2009; Hu et al. 2009; Moghaddam and Adjeroh 2010; Yaghmaee et al. 2013; Rezaee et al. 2014] are available too. Table VIII summarizes many existing BANs-specific and BANs related WSNs-centric transport protocols in terms of their key features and addressed QoS requirements. These protocols for WSNs/BANs offer congestion control (i.e., detection, avoidance) [Wan et al. 2011; Monowar et al. 2008; Wang et al. 2006a; Misra et al. 2009; Hu et al. 2009; Yaghmaee et al. 2013; Rezaee et al. 2014] or reliability [yih Wan et al. 2005; Park et al. 2008] or both [Shaikh et al. 2010; Gungor et al. 2008; Tezcan and Wang 2007; Akan and Akyildiz 2005; Iyer et al. 2005]. A number of WSNs-specific protocols [Wan et al. 2011; Wang et al. 2006a; Monowar et al. 2008; Park et al. 2008; Shaikh et al. 2010; Gungor et al. 2008; Tezcan and Wang 2007; Iyer et al. 2005] are useful in BANs/WBANs. COngestion Detection and Avoidance (CODA) [Wan et al. 2011] is an extension of [Wan et al. 2003] in terms of energy efficiency. The CODA is a congestion control protocol that employs receiver-based congestion detection scheme. The Priority Congestion Control Protocol (PCCP) [Wang et al. 2006a] and Prioritized Heterogeneous Traffic-oriented Congestion Control Protocol (PHTCCP) [Monowar et al. 2008] are cross-layered congestion control protocols, which offer higher throughput for higher priority traffic. But, non-critical or low-priority data may suffer higher delay and offer lower network throughput. In general, most congestion control protocols in WSNs/BANs are unable to offer reliability. On the contrary, reliable protocols GARUDA [Park et al. 2008] and Pump Slowly Fetch Quickly (PSFQ) [yih Wan et al. 2005] offers only reliability, which is limited for the communications from the sink/PS to sensor nodes. The Tunable Reliability with Congestion Control for Information Transport (TRCCIT) [Shaikh et al. 2010] uses packet rate to detect and rate adjustment to avoid congestion in WSNs. The TRCCIT exploits probabilistic adaptive retransmissions, hybrid acknowledgment, and retransmission timer management to provide probabilistically guaranteed tunable reliability. The Real-time and Reliable Transport (RT^2) [Gungor et al. 2008] provides congestion control as well as upstream reliability. Cross-layered RT^2 offers reliability and control congestion efficiently. However, reliability in RT^2 limited to sensors to the PS only. The Asymmetric and Reliable Transport (ART) [Tezcan and Wang 2007] mechanism supports congestion control and reliability. This is the only transport protocol listed in the Table VIII that supports reliable transfer of query or data from sink to sensors and sensors to sink. Event to Sink Reliable Transport (ESRT) [Akan and Akyildiz 2005] aims to provide reliability and congestion control in an energy efficient way. For reliability, it depends on PDR (packet delivery ratio) and congestion is managed passively without affecting reliability. The STCP (Sensor Transmission Control Protocol) [Iyer et al. 2005] is another WSNs-specific and sink controlled protocol that supports variable reliability and congestion control. For different applications, STCP offers different control policies to guarantee application requirements and improve energy efficiency.

The Learning automata-based congestion avoidance (LACAS) is a node-level congestion control scheme for BANs [Misra et al. 2009]. The LACAS controls node-level congestion by adaptively making the processing rate (data packet arrival rate) in the nodes equal to the transmitting rate (packet service rate). This improves only node-level throughput. Moreover, learning and historical data at sensor nodes could be energy and memory in-efficient. The Compression-based Congestion Control (CCC) [Hu et al. 2009] exploits compressive signal processing to extract bio-signal feature parameters and only transmit those parameters, which reduces communication traffic and minimize congestion. Transformation-based CCC may suffer due to scalability and recovery in unreliable communications [Razzaque et al. 2013]. Although, [Moghaddam and Adjeroh 2010; Farzaneh and Yaghmaee 2011; Yaghmaee et al. 2013] present different congestion control schemes, their main working principles are very similar, which is queue-based congestion control mechanism for high priority body sensor data. These mechanisms have the potential to offer higher throughput, lower delay for high priority traffic compared to [Wang et al. 2006a; Misra et al. 2009], but similar to [Wang et al. 2006a] low priority traffic may suffer delay and cause lower overall throughput. The Healthcare Aware Optimized Congestion Avoidance (HOCA) [Rezaee et al. 2014] is a data centric congestion management protocol using active queue management (AQM) for BANs. The HOCA first tries to avoid congestion in the routing level, if it is not possible then it does through an optimized congestion control algorithm.

Most existing BANs-specific transport protocols are congestion control protocols and utilize data or traffic prioritization for congestion control. In general, low-priority or non-critical data suffer higher delay and cause lower network throughput in priority-based congestion protocols for WSNs and BANs. On the contrary, most existing transport protocols for reliable transfer or congestion control and reliable transfer except ART [Tezcan and Wang 2007] offer one directional (i.e., sensors to sink/PS or sink/PS to sensor nodes) reliability. Existing WSNs-centric, even BANs-specific protocols are unaware of the real on and in body path losses and dynamic packet losses. Transport layer protocol like TCP may interprets packet losses as an indication of congestion and (inappropriately) invokes congestion control mechanisms, which leads to degraded performance. Inclusion of link-quality-awareness in transport layer protocols through cross-layer design can be useful in BANs [Razzaque et al. 2007].

4.1.5. Application layer. In tier one of a BAN, the application layer of a sensor or the sink or PS includes protocols and algorithms for various functionalities, including sensor and network management (e.g., synchronization), data management, data security, user interface, signal processing (e.g., compression), and data analysis. These protocols and algorithms can be grouped as a generic (e.g., sensor and network management protocol) or application-specific (e.g., compression as many applications may not allow compression) protocol. The application layer's protocols and algorithms, along with the other protocols, address QoS requirements (metrics), including DQ such as timeliness (latency), ubiquitous access, access security, and energy efficiency (e.g., compression), and resource quality ease-of-use/user-friendliness (e.g., user interface). Many research proposals have been published on each of the functionalities (e.g., compression, security) of the application layer [Lee et al. 2006; Diallo et al. 2012; Razzaque et al. 2013; Javadi and Razzaque 2013]. These proposals are mostly WSNs-centric. A comprehensive survey of these proposals is not within the scope of this article. Table IX summarizes the key functionalities of the application layer or their representative works, which could be useful for BANs/WBANs.

The Sensor Management Protocol (SMP) [Akyildiz et al. 2002] at application layer can be used for a BAN to interact with the body sensor nodes. This enables the lower layers to transparently interface with the application layer to take care of number of functionalities, including key management (security), clustering, time synchronization, and authentication. The Sensor Network Management System (SNMS) [Tolle and Culler 2005] is an interactive system for monitoring the health of sensor networks. The SNMS offers query-based network health data collection and event logging to offer energy efficiency and robustness. Real-time data management protocols are useful in BANs applications. A number of protocols for WSNs are published and surveyed in [Diallo et al. 2012]. The Real-Time Query Processing for Data Streams

Table IX. Summary of the existing Application Protocols or Algorithms for BANs

Application Protocol or Algorithm	Key Features	Addressed QoS	Remarks
SMP [Akyildiz et al. 2002]	Network Management, security, clustering, etc.	Energy efficiency, security	Too many functionalities by the same protocol
SNMS [Tolle and Culler 2005]	Query-based network health data collection and event logging	Energy efficiency, robustness	Not adaptive and scalable
RTSream [Wei et al. 2006]	Real-time data stream management, deals with deadline of queries	Timeliness	Centralized approach, does not provide the latest result of the incoming data stream
Real-Time Database Technique [Chagas et al. 2010]	Distributed and real-time data management using SQL-like language	Timeliness, energy efficiency, data consistency	Aggregation can cause delayed response
DMSDCM [O'Donoghue and Kennedy 2006]	Uses intelligent communication between mobile nodes, server and WSN/BAN	Timeliness, data consistency	Static patient assignment and lack of data classification
Data analysis (e.g., data mining) [McGrath and Scanaill 2013; Han et al. 2011; Yoo et al. 2012; Banaee et al. 2013; jin Kim and Prabhakaran 2013]	Extract unseen information from datasets	Data quality	Real-time response can be challenging
Fault Detection [Yang et al. 2015; Munir et al. 2015]	Detect sensor faults, offer fault tolerant system	Reliability	Detection delay is a concern
Data compression [Razzaque et al. 2013]	Reduce sensor level data size to minimize communication cost	Energy efficiency	Data quality and timeliness can be an issue
Security and privacy [Javadi and Razzaque 2013]	Offer information security, preserves users' privacy	Security, privacy	Complex security mechanisms can introduce delay and higher energy consumption
User interface [Zhong et al. 2006; Wong 2013]	Offer uses-friendly interacting environment for users	Ubiquitous access, ease-of-user	May conflict with security

(RTStream) [Wei et al. 2006] is a real-time data stream management protocol that deals with deadline of periodic queries over data stream. The RTStream offers periodic responses in real time without interrupting the query instance execution, but it is unable to provide the latest result of the incoming data stream because of the incoming data stream reported to next query instance. Authors in [Chagas et al. 2010] have presented a real-time database technique (RTDT) that uses SQL-like language. The RTDT employs in-network processing for energy efficiency. It also employs algorithms to maintain logical and temporal consistency of data. Aggregation of data may cause delayed response.

Data collected at application level need to be verified with appropriate data quality matrices (e.g., data consistency, completeness, believability) to extract useful and quality information for the applications [O'Donoghue and Kennedy 2006; O'Donoghue et al. 2008]. The Data Management System-Data Consistency Model (DMSDCM) intelligently interact with servers, mobile computing devices, and patient sensor nodes within a WSN/BAN to offer consistent and believable medical data. This is to ensure that medical practitioners receive up-to-date data on time every time. Data analysis tools, including data mining are used to reveal non-obvious patterns among the data and to determine data quality issues, such as outliers [McGrath and Scanaill 2013; Han et al. 2011; Yoo et al. 2012; Banaee et al. 2013; jin Kim and Prabhakaran 2013]. Extracting information from the BANs generated datasets, in particular, streaming body sensor data should be QoS-aware (e.g., timeliness) [McGrath and Scanaill 2013; Han et al. 2011]. Outlier detection and filtering, cleaning, plausibility testing could be useful in improving data quality [McGrath and Scanaill 2013]. Inaccurate data due to sensor faults or incorrect placement of sensors on the body could seriously influence clinicians' diagnosis, even could be catastrophic. Detection of sensor data faults has been widely researched in recent years [Yang et al. 2015; Munir et al. 2015] to develop reliable and trustworthy WSNs including BANs.

In medical and healthcare applications of BANs service differentiation or sensor data priority setting is an important phenomenon [Ameen et al. 2008]. This differentiation or setting depends on applications or users. The assigned priority setting or differentiation to physiological data should be adaptive to users' or application requirements. This means depending on the patient's age, sex, and clinical condition, the users should be able to change the assigned priority to a vital signal. For instance, glucose data might be assigned a low priority when the readings are in normal range, but a high priority might be reassigned to it by user when readings indicate hypo or hyper-glycemia. This QoS requirement of BANs is missing in most existing works and integration of it in the application layer is necessary. Moreover, the use of context-awareness in the application layer of a BAN is useful in providing QoS. Authors in [Wac et al. 2007] have already shown that the use of context information in BANs platforms can improve the delivered QoS [Wac et al. 2007]. Data compression in application layer could play a vital role in minimizing energy consumption and prolonging network lifetime. Distributed Source Coding (DSC), Predictive coding, and Compressed Sensing (CS) are examples of compression approaches to be useful in WSNs/WBANs [Razzaque et al. 2013]. CS is a new signal processing technique that holds great promise for energy efficient sensing and communication [Cand‘es and Wakin 2008; Razzaque et al. 2013]. CS and distributed CS are very efficient and effective signal acquisition methods in the context of a BAN. These methods could sample data from a sensor node at a lower rate, and later reconstruct from an incomplete set of measurements at the sink. Moreover, CS can offer data security through compressed signal [A.V. and Soman 2012]. The decoding complexity of CS and delay could be a concern in hard real-time applications.

An attractive graphic user interface is necessary to allow BANs' users (e.g., patient, doctor) to interact with BANs, in particular to instruct body sensors and display data received from those body sensors. The interface should be user friendly and ubiquitous for BANs users [Zhong et al. 2006; Wong 2013].

4.1.6. Cross-layer Design. The strict layering approach (TCP/IP protocol stack) was designed for wired network, and the assumptions in this stack are inadequate for wireless networking, including WSNs and WBANs [Razzaque et al. 2007]. In networking, cross-layer design attempts to share information amongst different layers, which can be used as input for algorithms, decision processes, and adaptations. In addition to performance (e.g., energy efficiency) improvements at different layers, cross-layering helps in developing QoS-aware applications in wireless networks including WBANs/BANs. It does so by providing high PDR, lower transmission delay, minimizing collisions and retransmissions, balancing energy consumption and reliable transmission in resource-constrained and dynamically (e.g., path loss) behaved WABNs.

Cross-layering can be done in different ways (e.g., creation of new interfaces, merging of adjacent layers). Most existing cross-layering approaches in WSNs or WBANs aim to achieve performance improvements through the optimization of two or more layers. Generally, these approaches are considered as loosely coupled or tightly coupled designs. Loosely coupled design approaches focus on adapting the parameters available at a lower layer to optimize the performance at a higher layer. In tightly coupled design approaches, different layers are optimized cooperatively to form one complete and better solution to an optimization problem. Typically, performance improvement in tightly coupled designs are greater than loosely coupled ones at the cost of protocol transparency and maintenance. A number of existing cross-layer design approaches for WBANs/WSNs are summarized below in terms of their potential QoS support in WBANs.

Cross-layering between MAC and Physical (PHY): The PHY and MAC layers of a WBAN/WSN are closely related, and their joint optimization can improve performance compared to their individual implementations. For instance, exploitation of the PHY layer's information, including remaining battery level and wireless channel's condition at the MAC layer of a WBAN can improve throughput, delay, and minimize collisions. The Channel Adaptive Energy Management (CAEM) protocol [Lin et al. 2007] in a sensor node to dynamically adjust data throughput by changing the levels of error protection at the node according to the quality of the link, estimated bandwidth, and traffic load. The CAEM buffers a packet until the channel recovers to the required quality, which can provide reliability in WBANs' dynamic channel conditions. This may come at the cost of inherent latency and potential buffer overflow due to the temporary storing of packets even with the scheduling based fairness policy. The cross-layering approach [Wang et al. 2008] between PHY and MAC layer of WBANs for healthcare monitoring application improves energy and spectral efficiency. This approach combines the adaptive modulation and coding (AMC) of the PHY layer and two sleep modes from the MAC layer to improve energy and spectral efficiency. The assumptions made in the approach about the received signals are unrealistic.

Cross-layering between PHY and Network Layers : Cross-layering between the PHY and Network layers of a WBAN/WSN are useful in improving the performances of routing and forwarding protocols in terms of energy efficiency, PDR, etc. In particular, these protocols exploit the remaining battery power information from the PHY layer. A number of existing routing protocols DMQoS [Razzaque et al. 2011], M-ATTEMPT [Javaid et al. 2013a], TMQoS [Muhammad Mostafa Monowar and Alamri 2014], RE-ATTEMPT [Ahmad et al. 2014], RAR [Bangash et al. 2014b], mentioned in the network layer section of this article, exploit the cross-layering between the PHY and network layers to improve energy efficiency, reliability, safety, etc.

Cross-layering between MAC and Network Layers : An optimal route can be found by exploiting information from the lower layers, such as traffic volume, link quality, and collision data. Authors in [Cui et al. 2005; Bouabdallah et al. 2009] have exploited cross-layering between the MAC and Network layers to gain energy efficiency in WSNs. The cross-layering between these layers mitigates the hidden node problem, provides configurable shortest path and energy efficiency in WBANs [Ruzzelli et al. 2007]. The Sleep Collect and Send (SCSP) protocol resolves the inherent conflict between energy efficiency and throughput, and improves energy efficiency and connectivity in compared to the 802.15.4 protocol. The ARBA [Ababneh et al. 2015] protocol, exploits cross-layering between the link and network layers to improve the utility, load balancing, and energy efficiency within a BAN.

Cross-layering between Transport, MAC and PHY Layers : A direct relationship exists between the PHY/MAC and transport layer. The cross-layer protocols have the potential to deliver higher throughput and minimal end-to-end packet delay by differentiating true congestion and MAC related packet drops. Spectrum sensing mechanisms operating at the lower layers can minimize interference and allows opportunistic access. This ultimately helps the transport layer to make more informed decisions on congestion and collisions in delivering reliable communications [Stabellini and Zander 2010]. A number of transport protocols (summarized in the Table VIII) including PCCP [Wang et al. 2006a], PHTCCP [Monowar et al. 2008] and RT^2 [Gungor et al. 2008] relied on cross-layering design approaches to minimize collisions and improve reliability in WBANs/WSNs.

Cross-layering between Application and MAC, PHY Layers: In a top-down approach, a user or BAN's/WBAN's application layer can inform the lower layers its QoS requirements (e.g., data reliability, delay tolerance). Even the application layer can force the lower layers of the WBANs to provide those QoS requirements if it is a critical application. In a bottom-up design approach, an application can adapt itself based on the MAC/physical layers information or resources of a WBAN. Rahman et al. [Rahman et al. 2008] have developed an adaptive cross-layer mechanism to control congestion for real-time and non-real time traffic and to support QoS guarantees at the application layer. Priority is given to the real time data in terms of delay and available link capacity. This approach interconnected the QoS requirements at the application layer and the packet waiting time, collision resolution, and packet transmission time metrics at the MAC layer. The Distributed Queuing Body Area Network (DQBAN) MAC [Otal et al. 2009] is an enhancement to the 802.15.4 protocol for WBANs. The DQBAN incorporates information from the PHY and Application layer along with a fuzzy rule scheduler that optimizes the MAC layer to improve overall performance in terms of QoS including energy consumption. Authors in [Garudadri and Baheti 2009] presented a solution that exploits cross-layering between application and MAC for packet loss mitigation in WBANs using a compressed sensing approach. The presented cross-layered solution offer high fidelity and very little latency in case of lossy ECG signals communications within a WBAN. The cross-layer design approach [Awad et al. 2013] uses the optimal encoding and transmission energy information to minimize the energy consumption for delay constrained WBANs. The proposed cross-layer framework, across Application-MAC-Physical layers, has the potential to deliver packets within their timeliness and distortion requirements.

4.2. Overview of the works on Tier 3

Every tier in a BAN introduces challenges, such as data storage and management (e.g., physical storage issues, availability and maintenance), interoperability, and availability of heterogeneous resources, access security (e.g., permission control), real-time and reliable data delivery, data interpretability and visualization, unified and ubiquitous access in the realization of the system. These challenges are directly related to the QoS support in BANs, and many DQ, including ubiquitous access, access security, reliability, and interpretability are directly related to the tier 3 of a BAN system. For instance, in a hospital, the number of patients using WABNs and the storage requirement for their data generated from the continuous monitoring can vary dynamically. Any static and conventional strategy will quickly become ineffective. Consequently, data loss (a QoS issue) is very likely in such situations, if timely elastic data storage mechanisms are not available [Doukas and Maglogiannis 2011]. However, this elastic data storage can be costly and might be under-utilized. Typically, the tier 3 of a BAN is implemented using a medical server [Otto et al. 2006; Natarajan et al. 2007a] and the traditional Internet. In recent years, many researchers and industries in health and medical care domain are considering cloud integrated BANs/WBANs [Shimrat 2009; Rolim et al. 2010; Koufi et al. 2010; Doukas and Maglogiannis 2011; Ahmed and Gregory 2011; Kuo 2011a; Mohapatra and Rekha 2012; Columbus 2014] because of many benefits, including elastic storage and processing, ubiquitous access, availability, fast responsive, and security, of cloud computing services over the traditional Internet.

The traditional Internet setting is unsuitable and inefficient to accommodate huge and elastic medical data (i.e., big medical data) generated from WBANs/BANs applications. Researchers [Koufi et al. 2010; Shimrat 2009; Rolim et al. 2010; Koufi et al. 2010; Doukas and Maglogiannis 2011; Ahmed and Gregory 2011] have identified the potential of cloud computing in terms of flexible data storage support for medical data and healthcare data. This can minimize the data loss occurring in traditional medical servers due to storage overflow [Doukas and Maglogiannis 2011; Kuo 2011b]. One key difference between the traditional Internet setting and cloud computing is the pay-as-you-go policy of the cloud computing. Moreover, all the hardware and software requirements will be on cloud service provider's side, which cut down the operational cost of hiring administrators to maintain servers, especially for those who are starting small and medium size healthcare organizations [Karthikeyan and Sukanesh 2012; Kuo 2011b]. The hardware failure due to aging, human errors resulting from overloaded works, and plenty of cut corners can cause service outages within a health or medical care organization. Service outages could lead to a catastrophic situation for the organization and patient. Disaster Recovery as a Service (DraaS) of cloud computing provides recovery services to its subscribers [Davis 2104]. With the DraaS, BANs data are available anytime and anywhere as it always keeps backup on the other clouds. With the advancement of the database management system, cloud computing makes the access and query to the data stored in different places easier and faster. Moreover, virtualization in cloud computing supports multi-tenancy for BAN users [Yuriyama and Kushida 2010]. Real-time response (timeliness) is a key QoS requirement for health and medical care applications of BANs. Fast response time of cloud can improve the multi-tenancy performance as multi-tenants (e.g., the BAN tenants) can use the cloud resources to get real-time responses. This is because of enough computing resources or servers provided by the cloud service provider to each of the clients. Generally, a cloud computing platform provides fast response time by running jobs in a batch with a very fast run time, which is very useful in health and medical care related big data. Moreover, virtualization and cloud computing facilitate platforms for more effective analysis and visualization of data to offer improved interpretability of data gathered from body sensors [Raghupathi and Raghupathi 2014; Klimov et al. 2015; Huang et al. 2015].

Along with a public cloud, a private cloud can be used as a backup mechanism for a health or medical care organization for disaster recovery of sensitive BANs data. As cloud computing offers ubiquitous access to data or service, health or medical care personnel of the organization can access medical data in a private cloud anytime from anywhere with higher security and better privacy than public clouds [Koufi et al. 2010]. On the contrary, the traditional Internet setting may not support ubiquitous access. However, many IT professionals believe that cloud computing has a much higher risk for data disclosure than the traditional Internet setting [Zissis and Lekkas 2012]. Researchers and vendors are working hard on minimizing the security and privacy risks in cloud computing environments [Wang et al. 2009b; Wang et al. 2011; Intel 2013]. For example, some of the vendors would have 24 hours network performance monitoring to prevent any intrusion action. Security of BANs data can be ensured by enabling public auditing service for cloud data storage [Wang et al. 2009a]. A third-party auditor (TPA) can be used by the cloud client to audit the outsourced medical data of the patients or caregivers shared on the cloud. Moreover, considering the criticality of medical applications private or hybrid cloud can be used as they support the Health Insurance Portability and Accountability Act (HIPAA) requirements and provide better data security [Ford 2013].

Many cloud-integrated BANs/WBANs infrastructures or solutions, including [Rolim et al. 2010; Doukas and Maglogiannis 2011; Fortino et al. 2012; Pandey et al. 2012;

Table X. Summary of the existing cloud-based Tier 3 solutions for BANs

Solutions	Key Features	Addressed QoS	Remarks
Cloud-based autonomous data collection [Rolim et al. 2010]	Automates the patient's data collection in healthcare institutes	Ubiquitous access, cost effective	Lacks data security
Cloud-based wearable textile [Doukas and Maglogiannis 2011]	A wearable textile platform relying an open cloud infrastructure	Scalability, ubiquitous access, interoperability	Lacks data security
BodyCloud [Fortino et al. 2012]	An architecture for the management and monitoring of body sensor data streams	Scalability, ubiquitous access, interoperability	Lacks data security
Autonomic cloud environment [Pandey et al. 2012]	Offers cloud processing and analysis of health related data	Scalability, ubiquitous access, interoperability, timeliness	Lacks data security
MCC-based EMS [Koufi et al. 2012]	An MCC-enabled emergency medical system	Ubiquitous access	Lacks data security
Cloud-enabled WBAN [Wan et al. 2013]	a MCC-enabled WBAN architecture for pervasive healthcare systems	Reliability, ubiquitous access	Lacks data security
Hybrid framework [Al-Qurishi et al. 2015]	Exploits mobile and multimedia cloud based framework for NCD patients	Ubiquitous access	No implementation
MC-ABE [Guan et al. 2015]	A secure access control mechanism for cloud-integrated BANs	Ubiquitous access, security	Not scalable
AIWAC [Chen et al. 2015]	An architecture uses emotional data to offer emotional and health care	Ubiquitous access	Unable to identify factors related to emotion

Wan et al. 2013; Al-Qurishi et al. 2015; Guan et al. 2015] have been proposed and implemented, especially in the last couple of years. Traditional processes for patients' vital data collection require a great deal of work to collect, input, and analyze the information. These processes are usually slow and error prone, introducing a latency that prevents real-time data accessibility. Authors in [Rolim et al. 2010] have proposed a solution to automate these processes exploiting sensors attached medical equipment that are inter-connected to exchange services. The lack of security and privacy solution of the proposal is a concern. In [Doukas and Maglogiannis 2011] authors have presented a wearable textile platform relying an open cloud infrastructure for monitoring and further processing of motion and heartbeat data. The platform aims to address data storage and management, interoperability and availability of heterogeneous resources, unified and ubiquitous access issues in WBANs. The proposed system is useful for remote monitoring of patient and elderly requiring constant surveillance. The BodyCloud [Fortino et al. 2012] is a cloud computing based system architecture for the management and monitoring of body sensor data streams. This supports scalability and flexibility of resources, sensor heterogeneity, and the dynamic deployment and management of user and community applications. Authors in [Pandey et al. 2012] have presented an autonomic cloud environment based healthcare monitoring system that collects users health data and disseminates them to a cloud-based information repository and facilitates analysis on the data using software services hosted in the cloud. A real-life implementation of the system highlights the potential of the system in analyzing healthcare related real-time data. The mobile cloud computing (MCC) integrated WBANs can offer tremendous opportunities for pervasive health and medical care systems. An MCC-based emergency medical system's (EMS) prototype is presented in [Koufi et al. 2012]. The medical system integrates the emergency service with personal health record systems to provide easy and ubiquitous access for physicians to patient data using any computing devices, including android devices. Another MCC-enabled WBAN architecture for pervasive healthcare systems is presented in [Wan et al. 2013]. This work has studied the functionality and reliability of MCC services in WBAN based pervasive healthcare system. Authors in [Al-Qurishi et al. 2015] presented a new hybrid (i.e., combination of mobile and multimedia) framework based on mobile multimedia cloud that is scalable and efficient, and provides cost-effective monitoring solution for non-communicable diseases (NCD) patients. They analytically showed that the hybrid framework outperforms the mobile or multimedia framework in terms of cost, reliability, security, scalability, and fault tolerance. Moreover, various health and medical care use cases demonstrated many potential benefits of big data analysis, including better and fast interpretation of medical data to improve medical and healthcare [Raghupathi and Raghupathi 2014].

Data access security in cloud-integrated BANs is an important and challenging issue because of the sensitivity of health and medical data. The Mask-Certificate Attribute-Based Encryption (MC-ABE) [Guan et al. 2015] is a novel secure access control mechanism for cloud-integrated BANs. The analysis shows that the MC-ABE proposed scheme has the potential to meet the security requirement of cloud-integrated BANs. This scheme requires less computational and memory overhead compared with other popular models. However, scalability of the mechanism can be a concern. Human-centric mechanisms for affective interactions are necessary for the effective utilization of BAN in various applications. The Affective Interaction through Wearable Computing and Cloud Technology (AIWAC) [Chen et al. 2015] is a novel architecture, which aims to exploit emotional data, collected through BANs, to offer emotional and health care. The AIWAC also includes enhanced sentiment analysis and forecasting models, and controllable affective interactions. This is a potential framework for providing emotional and health care services, but requires further research in directions, including finding the factors for emotional behaviors and how to control dynamic emotional interactions based on different context (e.g., locations).

Cloud computing is a potential solution for tier 3 of a WBAN/BAN, and it can address (Table X) many QoS issues, including ubiquitous access, scalability and interoperability. Many proposals, including [Klimov et al. 2015; Huang et al. 2015] showed how data analytics using cloud computing can be useful in visualizing, interpreting and offering better and faster medical and healthcare services. Issues, including slow response, operation visibility, trust, security and privacy of existing cloud computing solutions are still the main concerns for the wider adoption of it in critical applications, such as health and medical care.

5. OPEN RESEARCH CHALLENGES

Although the protocols and mechanisms presented herein address many issues in BANs' QoS (Figure 6), there are still number of open research challenges. Figure 6 presents the status of QoS issues addressed by existing proposals. Existing proposals support for QoS are insufficient (red colored in Figure 6) in most cases (e.g., safety, reliability, data security), or moderate for medical and healthcare applications. In the following we briefly present several open challenges related to QoS, categorized as data quality, communication, and resource quality in BANs.

5.1. Challenges related to Data Quality

Sensor Technologies and Sensors: The main provider of data quality. Generally, invasive sensing technologies offer better data quality, including accuracy and believ-

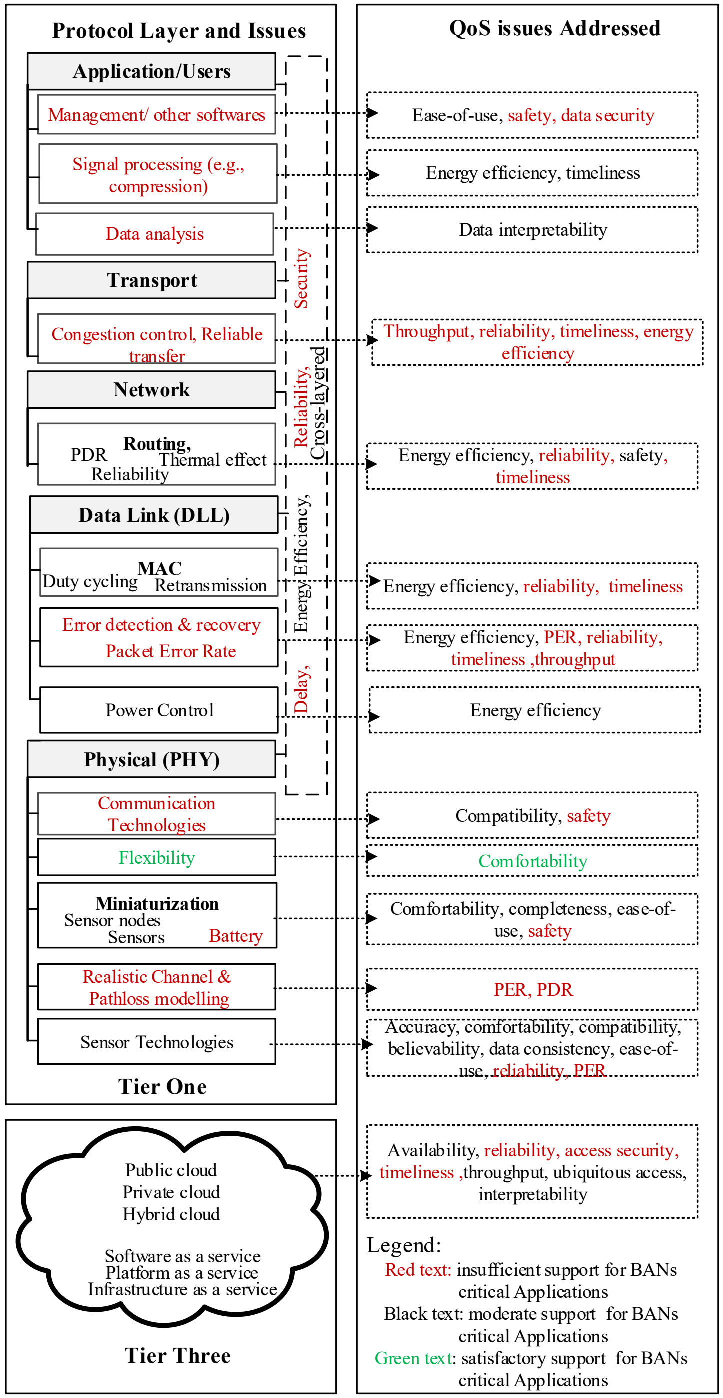


Fig. 6. Status of the existing QoS support in BANs (Tier 1 & 3)

ability, compared to their non-invasive counterparts. On the contrary, non-invasive sensors better suited for long-term and continuous monitoring (e.g., chronic disease monitoring). But, the absence of reliable non-invasive chemical sensors has greatly hindered the progress in the BANs. As an alternative, significant progress has been made in wearable electrochemical sensors and biosensors for real-time non-invasive monitoring of electrolytes and metabolites in sweat, tears, or saliva as indicators of a wearer's health status. These sensors generally produce data based on secondary measurements (e.g., blood sugar level from tears), which are, in general, less accurate and believable. This area needs further research and development. A non-invasive approach with infrequent and minimum invasive support could be a potential direction.

Context-Awareness: Context-awareness is necessary to provide quality in terms of complete, appropriate, and believable data through context-based adaptive data gathering. For example, a BAN-based chronic patient monitoring system needs to gather acceleration or event (context) data of users to make heart rate data believable and complete. Many existing data gathering techniques are non-adaptive or statically adaptive. Research is required for a context-aware and dynamically adaptive data gathering model. Moreover, context-aware coding (e.g., compression) and processing can improve timeliness in BANs by reducing communication delay. However, data redundancy removal principle of compression techniques contradict with data reliability. A context-aware tradeoff between these two can be a useful solution.

End-to-End QoS Requirements: Number of QoS requirements (e.g., timeliness, reliability, data security) in BANs need end-to-end (e.g., from sensors to the caregivers) support form a system. Most existing QoS solutions are technology-specific, BANs, mobile sensing, cloud computing, etc., and even within each technology solutions are communication layer-specific (e.g., QoS-aware routing, QoS-aware data gathering). Many BANs applications will use more than one of these technologies. Independent and non-cooperative QoS solutions of these heterogeneous technologies can be sub-optimal and insufficient for an application. Solutions should be holistic, and include cooperative supports from all the involved technologies and layers. Very little effort has been made in this area. There is clearly significant scope for future work in this area.

Data Security: All the concerns of security in all the technologies (e.g., wireless sensor networks, the traditional Internet, and cloud computing) used in BANs are clearly present in the context of the BANs. However, security and privacy are not completely resolved in these technologies. Being an end to end issue, existing layer-wise independent security solutions are insufficient for a number of BANs applications. Research for a holistic security solution that takes care of system as well as individual layer level security aspects is necessary. Also, this solution need to be privacy compliant. However, a complex and processing intensive security solution may contradict with energy efficiency and other QoS requirements (e.g., timeliness, safety, easy-to-use), which should be better understood and minimized. There is significant scope for future work in this area.

5.2. Challenges related to Communication

Communication technologies: The communication technologies of BANs can contribute to QoS in terms of energy efficiency, safety, reliability, and timeliness. However, most existing wireless communication technologies are not safe and energy efficient enough to be used in BANs. Considering the asymmetric nature of communications in BANs, use of different RF strategies for transmission and reception could be energy efficient. For instance, use of a UWB transmitter and a low-power narrowband receiver can save 50 and 500 folds energy per bit over conventional RF strategies [Calhoun et al. 2012]. The asymmetric radio architecture removes the broadcast channel concept that will affect protocols at all layers of the network stack. This will add complexity, which will require new protocols.

Realistic Channel and Pathloss Model: To provide non-interruptive services to wearers, BANs need to allow wearers' bodily motion. This will create dynamics in the wireless channel between sensor nodes and sink due to bodily obstructions and environmental changes. Most existing MAC or routing protocols are unaware of these dynamics of BANs and corresponding pathloss and packet losses. Even the protocols which are aware of these, do not consider the realistic channel and pathloss model. Without the realistic model of these two, useful and context-aware QoS support in BANs is impossible. Immediate research is necessary realistic channel and pathloss model.

5.3. Challenges related to Resource Quality

Miniaturization and Battery: The miniaturization of sensors and sensor motes is key in BANs to address many resource quality, including wearability, ease-of-use. These devices will eventually have very small volumes of 1 cm^3 or less. However, battery with sufficient energy density does not scale well down to these sizes. This is a challenging issue, especially in case of implanted BANs as they need both small size and long battery lifetime. This will be even more challenging in future generation nanosensors based BANs [Akyildiz et al. 2008]. Use of micro fuel cells and nanowire battery technology can increase in energy density and will result a smaller sensor node design. This will significantly prolong battery lifetimes over current power supplies.

Flexibility of BAN Devices: Flexible sensing devices are highly desirable in BANs. A significant advancement has been made on flexible devices. However, polymer based flexible devices need further development. Organic thin-film transistor based devices are preferable in e-skins due to inexpensive processing and high flexibility. But these devices suffer due to robustness and energy efficiency. On the contrary, inorganic nanowire circuits-based e-skins are energy efficient, mobile, and reliable, but require an expensive fabrication method. E-textile improves wearability, but the lack of direct contact of the sensing devices with the wearer skin is a concern for data quality. E-textile may also lose the typical textile properties such as flexibility or drapability. For on and in body wearable applications, adaptable on skin and organ interfaces needs to be investigated using biocompatible and flexible materials.

Safety: The safety in sophisticated applications of BANs has received little attention compared to other issues in BANs. The safety in BANs includes overall system level as well as individual components level (e.g., such as hardware, communication technologies, software). Typically, wearable applications need multidisciplinary support for QoS-aware and effective system. Conventional stove piped systems based technologies could be ineffective and unsafe. Systematic and multidisciplinary research is necessary to handle the safety challenges raised by the growing synergy of healthcare and engineering. Existing component-based works (e.g., sensors' material) of BANs individually address some aspects of safety, but the coordinating blueprint for ensuring interoperable and safe operation of the resulting system of those components is missing. The market demand for multi-functionalities within the BANs components (e.g., devices, software) may threat the safety of these components and the system. Studies are necessary to design and develop system-wide safety solutions for next generation critical and noncritical applications of BANs, which are aware of the complexities, intricacies and dynamics of the physical environment, and aware of users' behaviors, disease information, and related knowledge. Safety monitoring is also essential in critical applications [Calhoun et al. 2012].

6. CONCLUSION AND FUTURE WORK

Many applications of BANs, including health and medical care applications are real-time and life-critical, require strict guarantee of QoS., in terms of data, network, and resource quality. Many proposals have separately focused on these three aspects of QoS BANs. These proposals are diverse and involve different approaches or frameworks. This paper puts these proposals into perspective and presents a holistic view of the field. In this regard, this survey identified a set of QoS requirements for BANs applications and presented how these requirements are linked in a 3-tier BAN system. Based on the identified requirements, a review of the existing approaches and frameworks in tier one and three has been presented. Finally, open research issues, challenges, and recommended possible future research directions are outlined.

The identified QoS requirements, their related network metrics or parameters, and their providing tiers are presented as a taxonomy (Figure 4). Most QoS are linked to data quality as services are mainly based on processed data or information. Many of these QoS requirements are satisfied by one (e.g., energy efficiency depends power consumption) or more (e.g., timeliness is linked to PER, delay, delay jitter, bandwidth) network metrics. Each of these QoS requirements need support from one tier or more tiers (e.g., accuracy by T1, ubiquitous access by T2 and T3).

This survey reviews the existing works on tier 1 and 3 and their interactions with users (e.g., doctors, nurses, hospitals) of BANs. Moreover, existing works on tier one are highlighted according to their implemented layer of the BAN's protocol stack. Figure 6 presents the status of the existing QoS support in BANs (tier 1 & 3). Most sensors and sensors nodes are not sufficiently good enough to be used in acute and post-acute care applications. However, significant progress has been made in miniaturization and improving flexibility of sensors and sensor nodes to support wearability and ease-of-use through SoC, SoTs, e-skin, e-textile, etc. Existing wireless communication technologies are not safe and energy efficient for most BANs applications. The existing component-wise safety solutions (e.g., thermal-aware routing) are insufficient for most applications of BANs. Importantly, system-wide safety solutions for BANs are unavailable. A number of BAN specific MAC and routing protocols are proposed in the literature. Most of these protocols struggle to provide QoS in terms of timeliness, reliability in real-life BANs as they are unaware of users' context and dynamics of the BANs. Even the protocols which are aware of these, do not consider realistic channel and pathloss models. A limited number of BAN-specific transport and application protocols are available, which address QoS in BANs. A number of cross-layered protocols and approaches are proposed. Careful design of these protocols and approaches can help in supporting QoS of BANs. Finally, cloud computing in tier 3 of BANs applications is a potential alternative of the conventional Internet settings and servers. This can support elastic storage, ubiquitous access, availability, robustness, etc. for applications of BANs. Moreover, cloud-based big-data analysis can help caregiver in fast and better understanding and interpretation of medical and healthcare data.

Although the presented technologies, approaches, and protocols address many QoS requirements in BANs, some research questions remain relatively unexplored, such as context-aware adaptive data gathering, end to end data quality such as reliability, data security, component as well as system-wide safety analysis in BANs, realistic channel and pathloss model, miniaturization of battery with sufficient energy density. There is a significant scope for future work in these areas. Realizing the importance of the realistic channel and pathloss model, our future endeavors will focus on developing a context-aware realistic model for dynamic channel in BANs. This will also lead to the development of a realistic pathloss model in BANs. We also have the intention to explore component and system-wide safety and security analysis in BANs for medical and healthcare applications.

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