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MOBILE SYSTEMS

A comprehensive survey of energy-aware routing protocols in wireless body area sensor networks

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Abstract Wireless body area sensor network is a special purpose wireless sensor network that, employing wireless sensor nodes in, on, or around the human body, makes it possible to measure biological parameters of a person for specific applications. One of the most fundamental concerns in wireless body sensor networks is accurate routing in order to send data promptly and properly, and therefore overcome some of the challenges. Routing protocols for such networks are affected by a large number of factors including energy, topology, temperature, posture, the radio range of sensors, and appropriate quality of service in sensor nodes. Since energy is highly important in wireless body area sensor networks, and increasing the network lifetime results in benefiting greatly from sensor capabilities, improving routing performance with reduced energy consumption presents a major challenge. This paper aims to study wireless body area sensor networks and the related routing methods. It also presents a thorough, comprehensive review of routing methods in wireless body area sensor networks from the perspective of energy. Furthermore, different routing methods affecting the parameter of energy will be classified and compared according to their advantages and disadvantages. In this paper, fundamental concepts of wireless body area sensor networks are provided, and then the advantages and disadvantages of these networks are investigated. Since one of the most fundamental issues in wireless body sensor networks is to perform routing so as to transmit data precisely and promptly, we discuss the same issue. As a result, we propose a classification of the available relevant literature with respect to the key challenge of energy in the routing process. With this end in view, all important papers published between 2000 and 2015 are classified under eight categories including 'Mobility-Aware', 'Thermal-Aware', 'Restriction of Location and Number of Relays', 'Link-aware', 'Cluster- and Tree-Based', 'Cross-Layer', 'Opportunistic', and 'Medium Access Control'. We, then, provide a full description of the statistical analysis of each category in relation to all papers, current hybrid protocols, and the type of simulators used in each paper. Next, we analyze the distribution of papers in each category during various years. Moreover, for each category, the advantages and disadvantages as well as the number of issued papers in different years are given. We also analyze the type of layer and deployment of mathematical models or algorithmic techniques in each category. Finally, after introducing certain important protocols for each category, the goals, advantages, and disadvantages of the protocols are discussed and compared with each other.

Keywords Wireless body area sensor network · Routing · Energy-aware protocols

This article is part of the Topical Collection on *Mobile Systems*

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Introduction

The health of individuals is an important prerequisite to the health of communities, making health care a necessity for society that should be provided somehow. The quality of medical service if the number of elderly people increases would be most likely to drop, making health care and medical costs increase dramatically [1]. On the other hand, cardiovascular disease is the leading cause of death in the world, accounting for 30 % of all deaths. According to figures, almost 17.5 million people in the world die of heart disease each year. In addition, about 246 million people worldwide suffer from diabetes, and the number will reach 380 million by 2025 in the absence of proper health care and necessary preventive measures. The incidence of other diseases such as kidney problems, Alzheimer's disease, Parkinson's disease, anxiety disorder, and infant syndrome can be reduced by providing health care [2]. One of the health care strategies is to utilize advanced technologies in the medical field. In this regard, the body area network is a recently introduced technology which allows monitoring a person's health.

Advances in device miniaturization and power consumption reduction have caused the demand for body area networks to rise. The concept of body area network was first proposed by Zimmerman in 1996 and then defined by IEEE 802.15.6. The body area network creates a wireless network in the human body by radio frequencies. Based on the location where nodes are placed in or on the human body, body area networks can be divided into two categories, namely wearable body area networks and implantable body area networks [3].

Although medical applications of the body area network predominate, it can be used for other purposes such as athlete monitoring, soldier surveillance, and animal care [4].

There are different modes of data transmission and reception in the body area network, each of which has advantages and disadvantages. Two common modes of transmission are single-hop and multi-hop. Using multi-hop mode leads to sending data with high confidence and low energy consumption. As the multi-hop mode is introduced in body area networks, the concept of routing gains significant importance and should be examined properly. Routing is defined as sending data from its source to its destination in such a way that the conditions of directions are considered and data is delivered with enough confidence in such factors as delay and throughput. To achieve this goal, several routing protocols have been proposed, each of which is implemented with a view to improving certain criteria. Nonetheless, there are some challenges in routing, like network lifetime, reliability, delay, and resource constraints.

Routing protocols have various groupings which, in body area networks, include QoS-aware, thermal-aware, cross-layer protocols, opportunistic, and so on. Since wireless technology is used in wireless body area networks, a kind of contention takes place among nodes to access the network channel. In order to access the channel, a number of protocols have been presented that determine how to access the medium. They are called medium access control protocols and have particular importance in reducing energy consumption. It can be concluded that the wireless body area network is an appropriate piece of technology that has many applications in different fields, letting those carrying such a network enjoy considerable advantages. Due to the novelty and attraction of wireless body area networks, references in the field of data transmission are available in multi-hop mode; [5, 6] can be noted as examples. Cross-layer protocols, being actually a hybrid of routing and medium access control, have been discussed in [7].

Certain protocols in the field of energy and energy saving have been presented in [8–24]. An approach toward encoding body area networks by decode-and-forward relay strategy has been provided in [11]. In this method, each relay combines different messages from multiple sources to produce a single message, which is then sent to the intended destination. This method leads to reduced energy consumption. A leader selection mechanism to conserve energy has been proposed in [12]. A multi-modal power amplification method relying on antenna selection mechanism has been provided in [13] to improve network performance. [14] has examined packet size optimization for improving energy efficiency and accordingly has given models for packet error rate and energy efficiency in ARQ design. The use of the discrete wavelet transform and compressive sensing algorithms for scalable EEG data compression in wireless sensors has been introduced in [15] to address the power and distortion constraints. Energy efficiency requirements and performance in MAC protocols have been evaluated in [16]. A hierarchical network architecture, which integrates body area nanonetworks and health care monitoring systems and two different energy-harvesting protocol stacks, has been proposed in [17]. A method is proposed in reference [18] to reduce power consumption by data aggregation mechanism, which can be of high importance.

To reduce the energy consumption and overhead for relaying nodes, [19] has introduced a two-hop extension protocol which lets the resource-equipped hub directly transmit packets to the downlink relayed nodes. A reliable, energy-efficient protocol has been proposed in [20]. In forwarding data energy efficiently with load balancing in body area networks, a forwarder node is incorporated which reduces the transmission distance between sender and receiver to save energy in other nodes. A protocol for patient monitoring has been presented in [21], where some patients were investigated by positioning the sink at different locations or making it static or mobile. Akram and et al. suggested an energy-efficient protocol designed to measure fatigue in soccer players [22].

Cloud computing is an innovative method capable of assisting in storing, processing, analyzing, delivering, distributing, and securing crucial data [25]. Furthermore, Ahnn et al. [26] revealed that a mobile health monitoring application based on cloud computing is approximately 20 times faster and 10 times more energy-efficient than a standard one.

Table 1 Differences between wireless body area networks and wireless sensor networks

Issues	Wireless Sensor Network	Wireless Body Area Network
Scale	Monitored Environment (meters/ km)	Human body (centimeters/ m)
Node Number	Many redundant nodes for wide area coverage	Fewer, limited in space
Result Accuracy	Through node redundancy	Through node accuracy and robustness
Node Tasks	Node performs a dedicated task	Node performs multiple tasks
Node Size	Small is preferred, but not important	Small is essential
Network Topology	Very likely to be fixed or static	More variable because of body movement
Data Rates	Most often homogeneous	Most often heterogeneous
Node Replacement	Performed easily, nodes even disposable	Replacement of implanted nodes difficult
Node Lifetime	Several years/months	Several years/months, smaller battery capacity
Power Supply	Accessible and likely to be replaced more easily and frequently	Inaccessible and difficult to be replaced in an implantable setting
Power Demand	Likely to be large, energy supply easier	Likely to be lower, energy supply more difficult
Energy-Scavenging Source	Most likely solar and wind power	Most likely motion (vibration) and thermal (body heat)
Biocompatibility	Not a consideration in most applications	A must for implants and some external sensors
Security Level	Lower	Higher, to protect patient information
Wireless Technology	Bluetooth, ZigBee, GPRS, WLAN	IEEE 802.15.6

Particular attention has lately been directed toward integrating cloud computing into WBANs as a fresh approach. Integrating cloud computing with WBANs, which are a revolutionary technology offering convenient remote health monitoring, has newly garnered considerable attention as a novel method. Although cloud-based WBANs face significant challenges, security and authentication have become the focus of most recent studies [27–29]. In 2013, Jiang et al. [30] proposed a privacy enhanced authentication scheme for telecare medical information systems, but Kumari et al. [31] pointed out their scheme has confronted with stolen verifier attack, online password guessing attack and impersonation attack.

Relay nodes placement strategies for minimizing energy consumption have been outlined in [32]. A CSMA-based MAC protocol has been described in [33], and [34, 35] have proposed TDMA-based MAC protocols which are used in body area networks. Moreover, protocols dealing with mobility have been investigated in [36–39]. Medium access control protocols have been discussed in [40–43].

Mobile device's characteristics are used which allow for the use of medical resources on the cloud environment to find medical devices has been proposed in [23]. The digital signature is also proposed in this paper to ensure the security of information, and this can be useful for the confidentiality of information. A real-time cloud-based healthcare monitoring system is proposed in reference [24] that can be used to determine patients' own health status outside the hospital. Patient's mobility is also considered in this paper. A secure medical data exchange protocol based on cloud environment is proposed in reference [40]. This protocol uses mobile device's characteristics, allowing users to access medical resources conveniently. Reference [44] provides a review of the architecture, topology, and communications of the body area network. It also considers medium access control in the wireless body area network.

Having evolved from the wireless sensor network and the ad hoc network, body area networks take advantage of both networks; however, this does not mean that body area networks employ sensor network protocols and techniques. Considering various issues, body area networks are different from sensor networks [8]. Table 1 shows the difference between wireless body area networks and wireless sensor networks in terms of different issues.

Body area networks serve various applications in different fields, including medical, safety, security, sports, social networking, and entertainment. In fact, all applications are

Table 2 Body area network applications

Medical applications	Non-medical applications
Disability assistance (rehabilitation), Remote control of medical devices, Human performance management, Hearing aid, Patient monitoring inside and outside the hospital, Bio-signal sensing (EEG, ECG, EMG, temperature, respiration, heart rate, etc.)	Gaming applications, Social networking, Entertainment applications, Smart key, Video streaming, Data file transfer

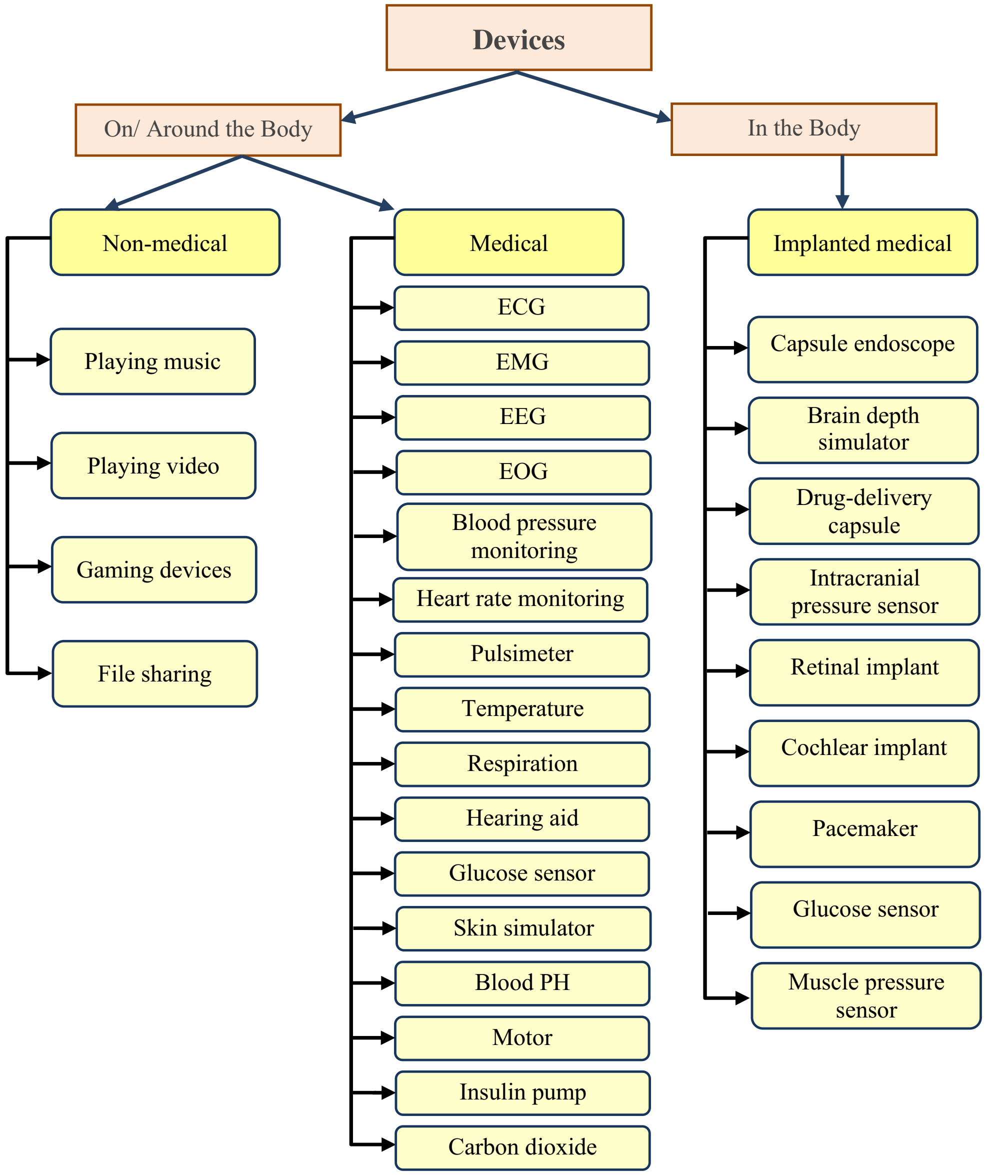


Fig. 1 Medical applications of nodes and sensors

classified into two categories: (1) medical applications and (2) non-medical applications. A classification of the body area network applications is shown in Table 2 [8]. Figure 1 outlines the applications of the nodes in body area networks.

Challenges in body area networks can generally be divided into two categories:(1) general challenges, which face the body area network; and (2)specific challenges, which are presented by the use of BANs in a particular field.

This paper analyzes the challenges of routing, which fall into the second category (i.e. specific challenges).

Since this paper focuses on routing with the aim of reducing energy consumption in sensor nodes, some challenges like network lifetime, unpredictable postural movement, temperature awareness, security and reliability should be consider in WBASN's energy aware routing protocols and we try to classify them.

In this paper, firstly, we discuss basic concepts of wireless body sensor networks. Then, after the routing challenges are explained, papers dealing with energy-efficient routing protocols are classified under eight categories. We also evaluate them by category. Furthermore, the process of researches conducted on energy-efficient routing is closely studied. Next, the goals, advantages, and disadvantages of the protocols are examined. In the end, important protocols in each category are thoroughly explained.

Classification of routing protocols with respect to energy

Since energy is one of the most important challenges to body area networks, energy routing protocols are examined and

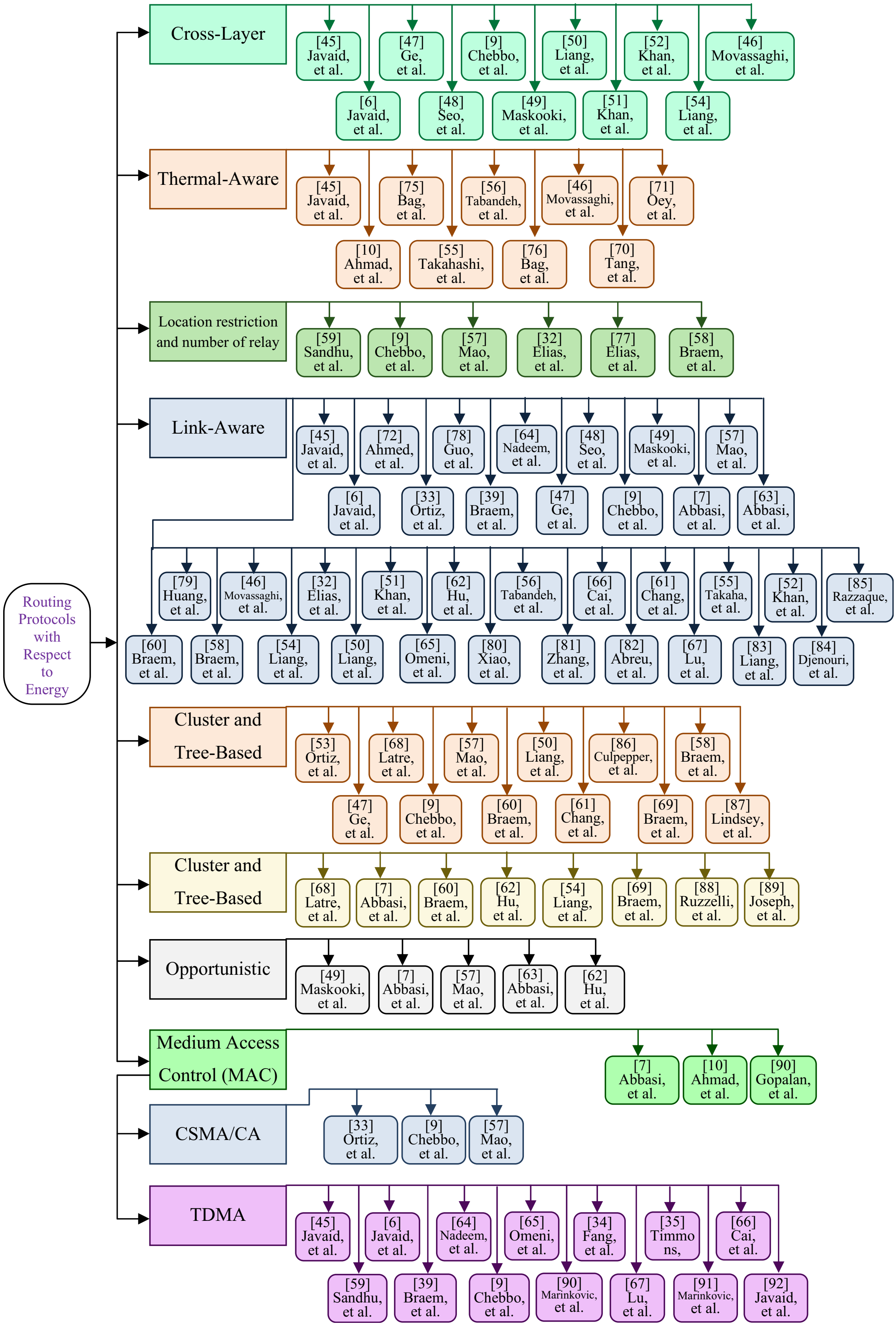
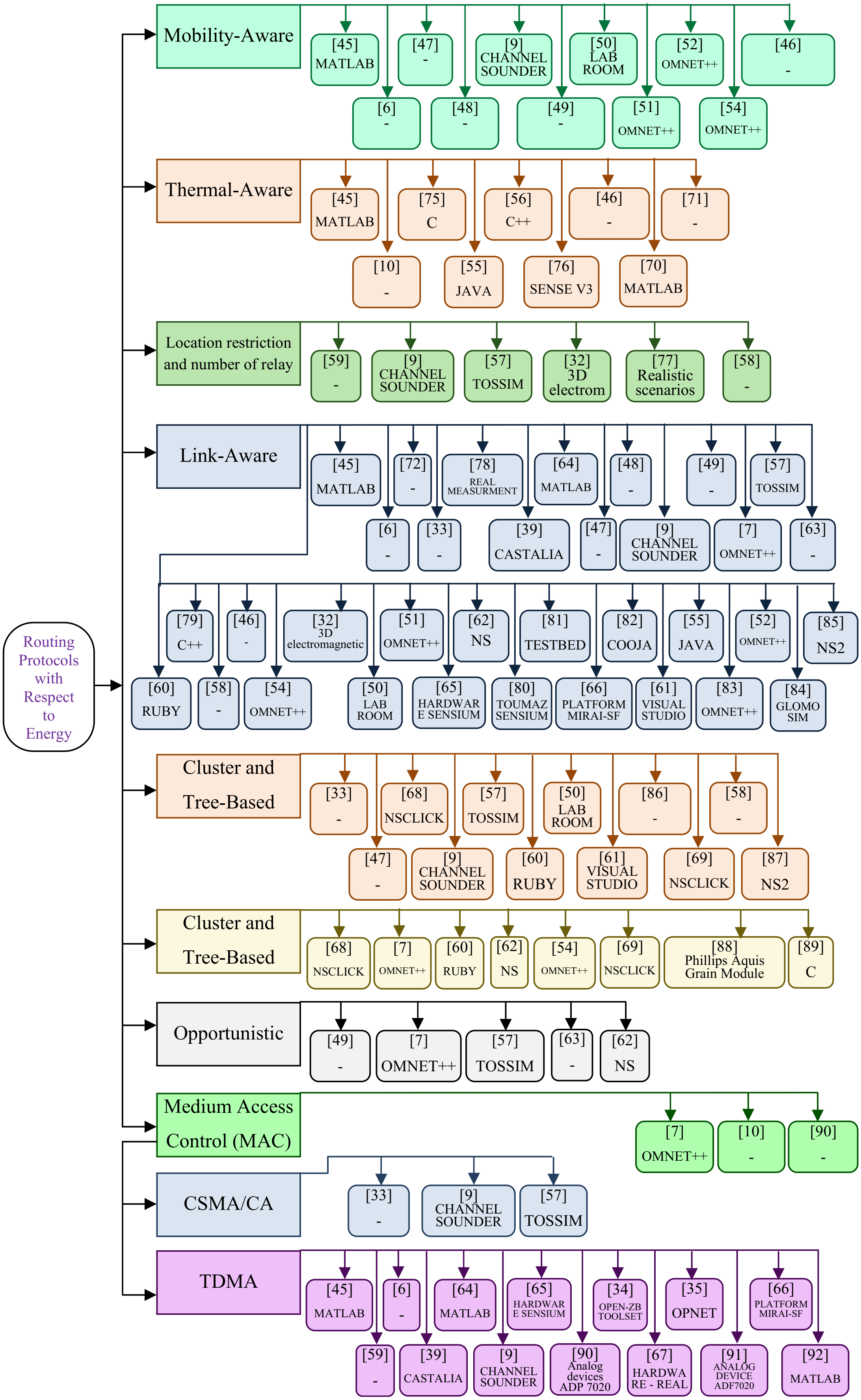


Fig. 2 Classification of routing protocols in body area networks with respect to energy


Routing Protocols with Respect to Energy
Mobility-Aware
[45] MATLAB
[47] -
[9] CHANNEL SOUNDER
[50] LAB ROOM
[52] OMNET++
[46] -
[6] -
[48] -
[49] -
[51] OMNET++
[54] OMNET++
Thermal-Aware
[45] MATLAB
[75] C
[56] C++
[46] -
[71] -
[10] -
[55] JAVA
[76] SENSE V3
[70] MATLAB
Location restriction and number of relay
[59] -
[9] CHANNEL SOUNDER
[57] TOSSIM
[32] 3D electrom
[77] Realistic scenarios
[58] -
Link-Aware
[45] MATLAB
[72] -
[78] REAL MEASUREMENT
[64] MATLAB
[48] -
[49] -
[57] TOSSIM
[6] -
[33] -
[39] CASTALIA
[47] -
[9] CHANNEL SOUNDER
[7] OMNET++
[63] -
[79] C++
[46] -
[32] 3D electromagnetic
[51] OMNET++
[62] NS
[81] TESTBED
[82] COOJA
[55] JAVA
[52] OMNET++
[85] NS2
[60] RUBY
[58] -
[54] OMNET++
[50] LAB ROOM
[65] HARDWARE SENSIUM
[80] TOUMAZ SENSIUM
[66] PLATFORM MIRAI-SF
[61] VISUAL STUDIO
[83] OMNET++
[84] GLOMO SIM
Cluster and Tree-Based
[33] -
[68] NSCLICK
[57] TOSSIM
[50] LAB ROOM
[86] -
[58] -
[47] -
[9] CHANNEL SOUNDER
[60] RUBY
[61] VISUAL STUDIO
[69] NSCLICK
[87] NS2
Cluster and Tree-Based
[68] NSCLICK
[7] OMNET++
[60] RUBY
[62] NS
[54] OMNET++
[69] NSCLICK
[88] Phillips Aquis Grain Module
[89] C
Opportunistic
[49] -
[7] OMNET++
[57] TOSSIM
[63] -
[62] NS
Medium Access Control (MAC)
[7] OMNET++
[10] -
[90] -
CSMA/CA
[33] -
[9] CHANNEL SOUNDER
[57] TOSSIM
TDMA
[45] MATLAB
[6] -
[64] MATLAB
[65] HARDWARE SENSIUM
[34] OPEN-ZB TOOLSET
[35] OPNET
[66] PLATFORM MIRAI-SF
[59] -
[39] CASTALIA
[9] CHANNEL SOUNDER
[90] Analog devices ADP 7020
[67] HARDWARE - REAL
[91] ANALOG DEVICE ADF7020
[92] MATLAB

◀ **Fig. 3** Deployed simulators by energy-aware routing protocols in wireless body area networks

compared in this paper. A general classification of the protocols is shown in Fig. 2. Due to the importance of energy in the body area network, the network may be highly efficient and acquire the ability to function for several years or months if the sensors are adjusted and designed very well and energy is properly managed. So with this end in view, we analyze the proposed energy-efficient protocols in the literature, with each protocol evaluated based upon different factors and criteria. Mainly dealing with investigating current protocols in body area networks with respect to energy, which are classified into 8 categories according to the applications benefiting from them and the improvements they make to different layers.

A classification of routing protocols has been provided in [8] based on temperature, mobility, and quality of service, cross-layer, and energy efficiency; however, there are several debatable points in it. First, only a small number of protocols have been classified while the importance of routing protocols requires that more protocols should be studied to properly make a logical comparison. Second, the protocols have been classified merely with the aim of practical grouping, whereas here we classify routing protocols from an energy perspective as energy plays a decisive role in network functionality and individual welfare. Finally, to precisely determine the nature of each protocol, we classify the protocols into the following 8 groups: mobility-aware, thermal-aware, protocols based on location restriction and number of relay, link-aware, cluster-based and tree-based protocols, cross-layer, opportunistic, and medium access control. As mentioned earlier, if a body area network is in a desirable condition in terms of energy consumption, it can operate for many years, without the need for recharging or battery replacement. This is particularly important for the nodes implanted inside the body, because they can disturb the patient's comfort if the required energy of the nodes is not managed properly. The main reason behind the current classification of routing protocols is to provide an explicit introduction and breakdown of the protocols which have improved the performance of body area networks through low energy consumption.

The importance of each group, the reason for making this kind of classification, and protocols related to specific categories will be explained later in the paper.

Body area network is a new technology that has significantly developed in recent years. Researchers from different disciplines have attempted to provide various protocols for improving the network. Hence, this research paper strives to consider the issues of routing and energy in body area networks, which are of particular importance in order to improve the network. Fortunately, with respect to energy in body area networks, different protocols have been proposed depending on their applications (the use of thermal-awareness, mobility), methods (opportunistic, cross-layer), and operational areas. Mobility is the first category in our classification of protocols. The reason for considering this category is that, since body area networks have special applications in the medical field, the patient needs to be capable of moving easily and comfortably. So, the patient can be monitored for a long period of

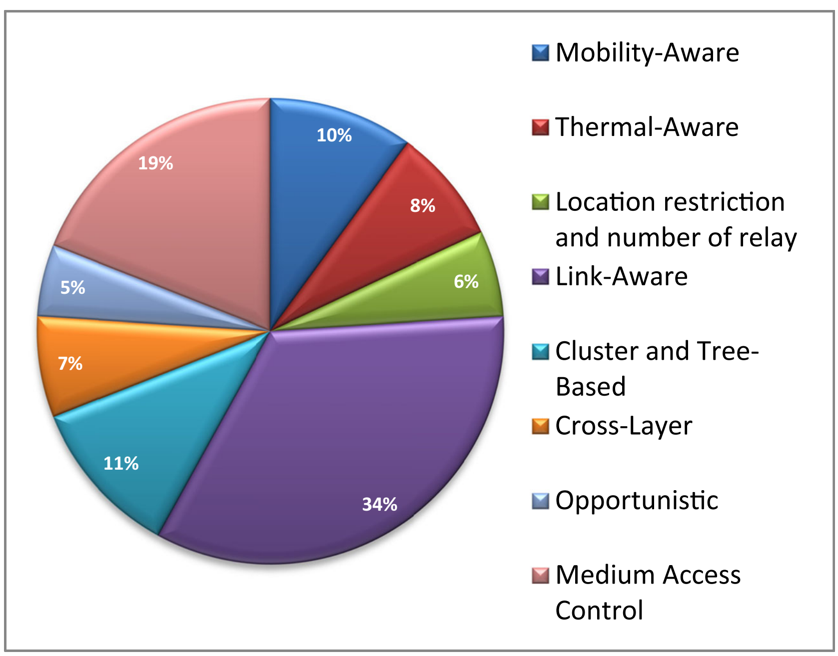


Fig. 4 Analytical chart of operational areas of the papers

Table 3 Hybrid protocols

Type of protocols	Mobility-aware	Thermal-aware	Location restriction and number of relay	Link-aware	Cluster and tree-based	Cross-layer	Opport-unistic	Medium access control
Mobility-Aware	-	[45, 46]	[9]	[45, 6, 47, 48, 9, 49, 50, 51, 52, 54, 46]	[9, 47, 50]	[54]	[49]	[6, 9, 45]
Thermal-Aware	[45, 46]	-	-	[45, 46, 55, 56]	-	-	[10]	[10, 45]
Location restriction and number of relay	[9]	-	-	[9, 32, 57, 58]	[9, 57, 58]	-	[57]	[9, 57, 59]
Link-Aware	[6, 9, 45–52, 54]	[45, 46, 55, 56]	[9, 32, 57, 58]	-	[9, 33, 47, 50, 57, 58, 60, 61]	[7, 54, 60, 62]	[49, 57, 62, 63]	[6, 7, 9, 33, 39, 45, 57, 64–67]
Cluster and Tree-Based	[9, 47, 50]	-	[9, 57, 58]	[9, 33, 47, 50, 57, 58, 60, 61]	-	[60, 68, 69]	[57]	[9, 33, 57]
Cross-Layer	[54]	-	-	[7, 54, 60, 62]	[60, 68, 69]	-	[62]	[7]
Opportunistic	[49]	[10]	[57]	[49, 57, 62, 63]	[57]	[62]	-	[10, 57]
Medium Access Control	[6, 9, 45]	[10, 45]	[9, 57, 59]	[6, 7, 9, 33, 39, 45, 57, 64–67]	[9, 33, 57]	[7]	[10, 57]	-

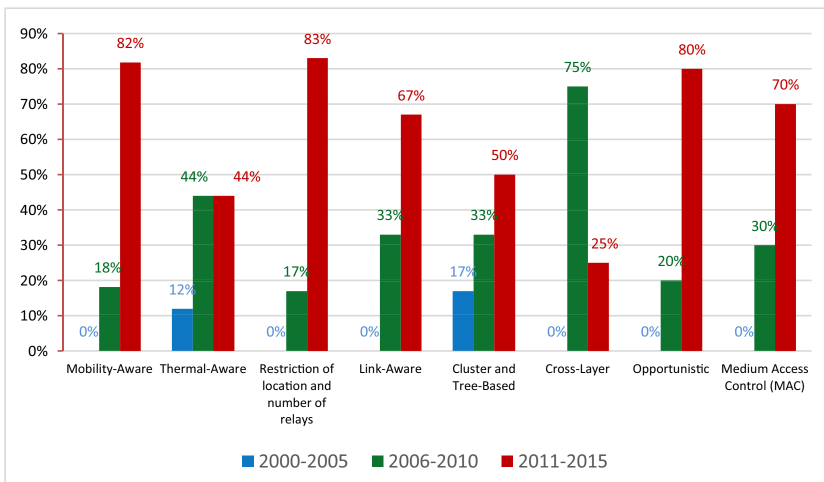


Fig. 5 Percentage distribution of papers for each category over five-year periods from 2000 to 2015

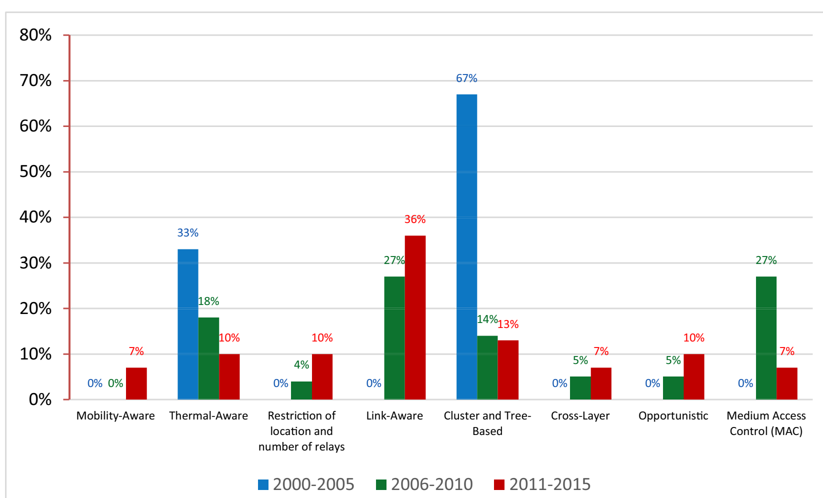


Fig. 6 Percentage distribution of papers in compared with other categories over five-year periods from 2000 to 2015

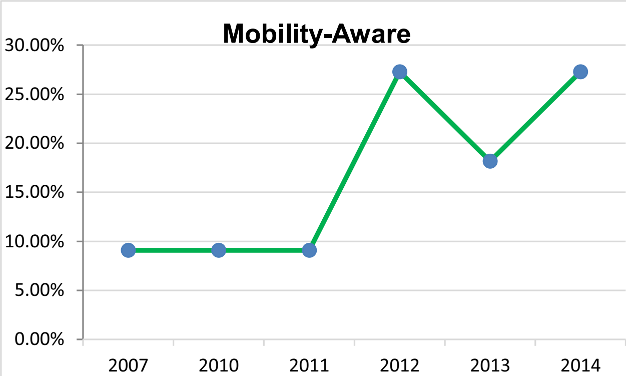


Fig. 7 Percentage of the papers in Mobility-Aware category released in separate years

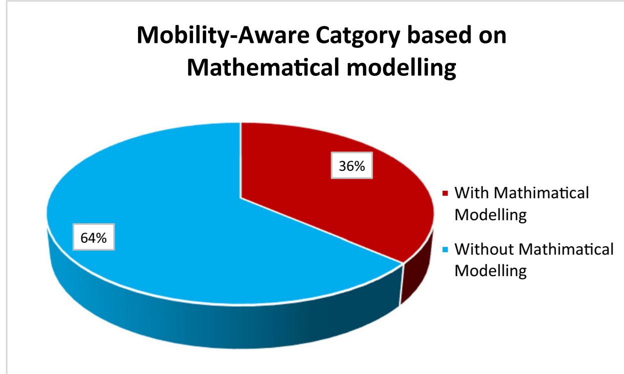


Fig. 9 Breakdown of Mobility-Aware papers in terms of mathematical models deployment

time, using this feature. Sensor nodes in body area networks perform different activities, such as sensing, which produce heat in the human body. On the other hand, the heat and radiations produced by the sensor nodes might cause damage to human tissues. Thus, some mechanisms need to be provided to prevent temperature rise in the nodes. With this aim in view, a category named 'Thermal-aware' has been included in the proposed classification, in which different heat routing protocols are examined. The third category, named 'Location restriction and Number of relay', deals with the breakdown of protocols that investigate the placement of additional and cooperative relay nodes in the body. 'Link-aware' is the name given to the fourth category, which includes protocols that somehow deal with the link status between the transmitter and the receiver and exchange data and information. Protocols that make use of cluster and tree for data transmission between origin and destination and are used for the timing of nodes fall into the next category called 'Cluster- and Tree-based protocols'. The sixth category has been dedicated to 'Cross-layer' protocols, which deploy a combination of several layers, including network layer and transport layer, to improve body area networks. 'Opportunistic' protocols constitute another category of the classification. These protocols focus on how sensor nodes gain access to the communication channel. Since getting access to medium in body area networks is immensely important in energy consumption and cost, 'Medium access control' has been mentioned as the last category, where protocols have been divided into two subcategories of random protocols and scheduled protocols according to the access to the communication channel.

Later in this paper, we will present a statistical analysis of each category in addition to providing more details about it. Furthermore, simulators deployed in each paper, together with the relevant category, are shown in Fig. 3 so that one can concentrate on certain simulators to improve each method.

Based on Fig. 2, where papers have been classified into 8 categories, Figure 4 indicates dispersion of papers and their association with specific areas.

According to the graph, papers focusing on link-aware protocols account for 34 % of all studied papers, which is the highest percentage. As mentioned in the previous sections, the 'Link-aware' category includes papers pertaining to the link status between the transmitter and receiver. In other words, any protocol that considers the link status for the improvement of body area networks has been included in this category. Since the link status has direct impact on various factors such as delay, packet delivery ratio, energy consumption, retransmission, and reliability, so many papers have been proposed in this area. The 'Medium access control' category has the second largest percentage (i.e. 19 %) of the papers. This area has received attention because channel access mechanism is of huge importance in the wireless body area network and other wireless networks. Papers studying 'Cluster- and Tree-based' protocols, which are effective in improving wireless body area networks because of using tree-based methods

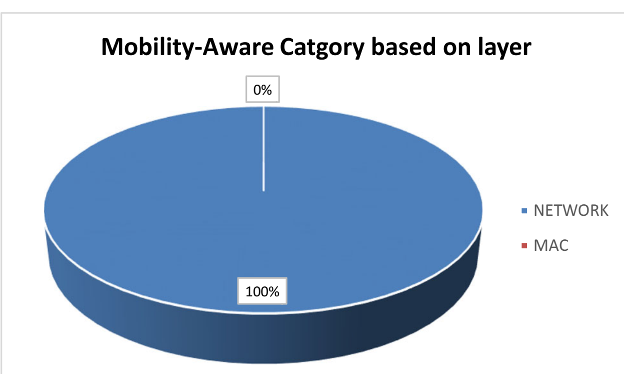


Fig. 8 Breakdown of Mobility-Aware papers in terms of layering

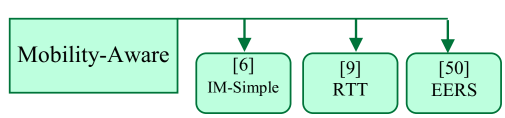


Fig. 10 Selected protocols from the 'Mobility-aware' category

Table 4 Comparison of the selected protocols from the 'Mobility-aware' category

Protocol	Goal	Advantages	Disadvantages
IM-SIMPLE	Reducing energy consumption	Has better stability period, network lifetime, throughput, and energy consumption	Has high packet drop
RTT	Reliable data transfer across the body area network	Has high reliability under slow-fading conditions	Using a large number of relays will result in the patient's discomfort
EERS	Achieving higher reliability and energy efficiency	Has high network lifetime, lower energy consumption, and low delay	Has high overhead in adaptive transmission power

for allocating slots to nodes and also for gathering data, comprise the third largest percentage of all papers. This category also considers protocols that employ clustering methods and therefore lead to reducing energy consumption. The 'Mobility-aware', 'Thermal-aware', 'Cross-layer', 'Restriction of location and number of relay' (relay node location), and 'Opportunistic' categories make up 10, 8, 7, 6, and 5 % of the papers, respectively. It is essential to note that these results were obtained from investigating 55 research papers and that percentages are likely to change if a larger number of papers are covered. Since some protocols fall into more than one of the categories in the proposed classification in Fig. 2, papers dealing with hybrid protocols are introduced in Table 3. For example, the proposed 'Mobility-aware' protocol in [6] investigates link status and medium access control and thus is qualified to be classified under 'Link-aware' and 'Medium Access Control' categories; such protocols are called hybrid protocols in this paper.

Figure 5 demonstrates the proportion of papers in each of the eight categories over successive five-year periods from 2000 to 2015. Analysis of the chart reveals that a very tiny minority of papers in each category were published between 2000 and 2005, with the sole focus of papers remaining on Cluster-Tree-Based and Thermal-Aware routing protocols during this period. Overall, there was a significant rise in papers between 2006 and 2010, specifically for Cross-Layer, Thermal-Aware, Cluster-Tree-Based, Link-Aware, and Medium Access Control categories. Moreover, there were suitable papers in all fields in 2011–2015. With respect to Link-Aware category, in particular, research papers doubled in percentage compared to the preceding five-year period. It should be noted that calculated percentages represent the proportion of papers released during different periods in each category to total papers in the same category. Furthermore, there was a higher growth in the number of papers looking at Medium Access Control than in that of other papers. Mobility-Aware was the second category to experience a significant rise in papers. As for energy in body area networks, packet delivery with higher reliability and how a connection is established between nodes are of overwhelming importance, so special attention has been devoted to Link-Aware category. Various studies have also been carried out on Medium Access Control because interference-free medium access, along with reducing energy consumption and deploying proper sleep/wake up mechanisms, is imperative (Fig. 6).

Effective factors in each category will be mentioned below. Some protocols from each category will also be introduced as there are different protocols in each category.

Mobility-aware protocols

These protocols focus on movements of the patient, such as motions of the hands, immobility, walking, running, and sleep modes. This category has been mentioned due to the special importance of mobility in body area networks. Selected from the general classification as instances of these protocols, [6, 9, 50] will be introduced in this section.

A line graph is given in Fig. 7 that indicates the years when the papers in Mobility-Aware category were published. According to Fig. 7, nearly 27 % of the papers in Mobility-Aware category were presented in 2012. Moreover, papers belonging to Mobility-Aware category are classified in Fig. 8 based upon layering (network and medium access control layers). As seen in Fig. 8, all investigated

Table 5 Qualitative comparison of protocols

Protocol	Stability Period	Network Lifetime	Energy Consumption	Throughput	Packet Drop	Path Loss
IM-SIMPLE	Good	Intermediate	Good	Good	Intermediate	Good
SIMPLE	Intermediate	Good	Intermediate	Intermediate	Good	Good
M-ATTEMPT	Poor	Good	Intermediate	Poor	Poor	Intermediate

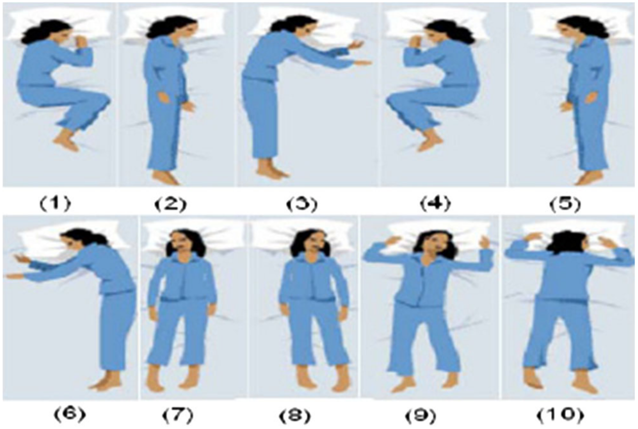


Fig. 11 Ten sleeping positions [9]

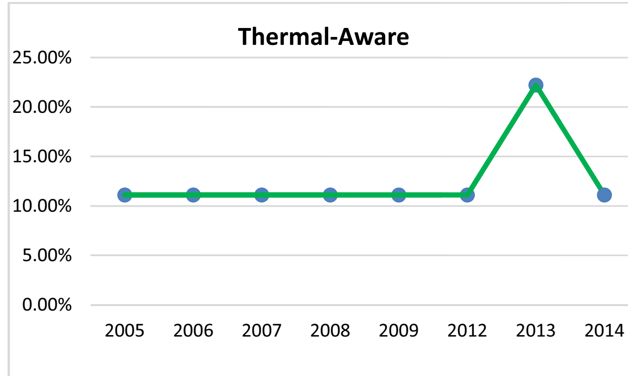


Fig. 12 Percentage of the papers in Thermal-Aware category released in separate years

papers were in the network layer and in the field of routing. Fig. 9 illustrates the status of mathematical models deployment in this category.

The selected protocols from the 'Mobility-aware' category are shown in Fig. 10; they are also compared in Table 4 in terms of advantages, disadvantages, and goals. Given the large number of protocols in each category, only a few numbers of them have been chosen to be discussed because of some reasons that will briefly be explained. The reason for choosing IM-SIMPLE protocol is to examine mobility in both sides of the arms. Another reason is that this method has yielded better results compared to the M-ATTEMPT method. The RTT protocol has been selected because it examines an individual in sleeping position and also considers different power consumptions in different topologies. Giving consideration to mobility in three modes (i.e. being static, walking, and running) with different transmission powers, the EERS protocol has been chosen. This paper also improves its previous method.

IM-SIMPLE is a protocol provided in a multi-hop mode for the body area network. The IM-SIMPLE protocol is an improved version of the SIMPLE protocol and was proposed because mobility and mathematical model for reducing energy consumption and increasing throughput had not been considered in the simple protocol.

Since this protocol uses short packets for communication and also considers residual energy and distance from the sink while selecting a forwarder node, it affects link situation and therefore has been classified under the 'Link-aware' category. On the other hand, this protocol has given consideration to mobility, as it is an important and necessary issue in body area networks. In this protocol, hand mobility is examined as the patient moves his hands to the left and right side of his body. This reduces packet drop and thus will significantly affect throughput and energy consumption.

Concerning network lifetime, stability period, throughput, and minimum energy consumption, this paper has performed better than simple and M-Attempt [6]. Since this protocol employs TDMA mechanism and also considers the amount of energy and the closest node to the sink for data routing, it has been classified under TDMA grouping. The proposed method is compared with other methods in terms of various factors in Table 5.

RTT Protocol focuses on Restricted Tree Topology (RTT), which implies a two-hop network with relays serving as the interface between nodes and the sink. Only when it is needed to solve the problems of restricted energy and high propagation loss, and also when improving reliability is concerned, RTT method deploys a star topology. This method investigates the presence of links between nodes through the received signal strength indicator (RSSI). Considering human sleep and the need that the patient should be monitored even in the sleeping mode, this paper examines 10 sleeping postures in patients resting in hospital beds, as shown in Fig. 11. This examination of sleeping positions involves analyzing link experience and link attenuation. Because of considering the multi-hop topology based on a tree, this protocol falls into the 'Tree- &

Table 6 Qualitative comparison of protocols

Protocol	Energy consumption	Path Loss/ packet drop	Packet reception ratio	Reliability	Delay	Overhead
EERS	Lower than the compared method	Lower than the compared method	Is 0.96 at adaptive transmission power	Better than CTP method	Low compared to that of the compared method	High
CTP	High compared to EERS method	High compared with EERS method	Ranges between 0.96 and 0.99 at a transmission power of 0	Lower than EERS method	High compared with that of EERS method	Low

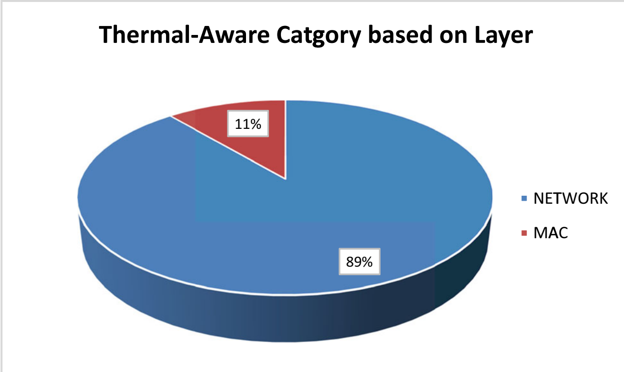


Fig. 13 Breakdown of Thermal-Awarepapers in terms of layering

Cluster-based' category. The present paper assumes a beacon-enabled network where the medium access control (MAC) sub-layer has a super-frame structure that is divided into a contention period, a contention-free period, and an optional idle period. RTT method is believed to be able to manage energy and improve reliability, using opportunistic and dynamic relays.

EERS Protocol is used a multi-hop mode for transporting the data. This paper concentrates on the Collection Tree Protocol (CTP), which is used for data collection in wireless sensor networks. The basic idea of CTP is to build one or more collection trees, each of which is rooted at a sink. Sensor nodes in a tree use stop-and-wait ARQ with a maximum of M retransmissions. In this condition, each node not only sends its own data, but also forwards data for other nodes. CTP is suitable for the body area network. Among other advantages, CTP has low complexity, low overhead, and robustness.

A comparison between EERS and CTP in terms of different factors is shown in Table 6.

Thermal-aware protocols

Since the nodes in body area networks produce heat that, if excessive, will damage body tissues, exploring protocols dealing with node temperature deserves particular attention, which is why the 'Thermal-Aware' category has been developed.

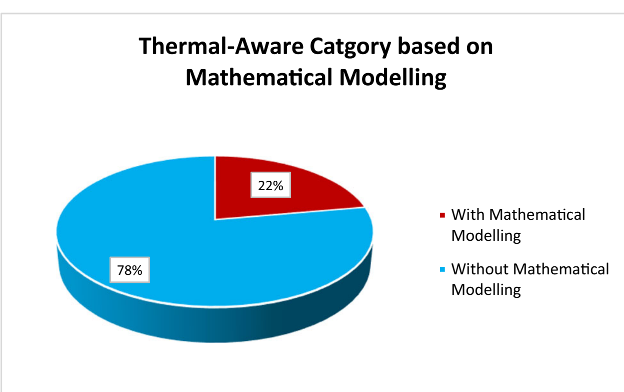


Fig. 14 Breakdown of Thermal-Aware papers in terms of mathematical models deployment

A line graph is presented in Fig. 12 that indicates the years when the papers in Thermal-Aware category were published. Approximately 22 % of the papers in Thermal-Aware category were published in 2013. Furthermore, Figure 13 provides a breakdown of the papers in Thermal-Aware category based on layering (network layer and medium access control layer). 89 % of the investigated papers belonged to the network layer, and 11 % of them fit into the medium access control layer. Figure 14 illustrates the status of mathematical models deployment in Thermal-Aware category.

The proposed protocols in references [10, 55, 56, 70] are introduced in this section as selected protocols from the general 'Thermal-aware' category (Fig. 15). Kamal and et al. proposed a new Fault Tolerant Virtual Backbone for Minimum Temperature in Sensor Networks that it can use in other thermal aware methods [53].As shown in Table 7, the selected protocols are also examined in terms of advantages, disadvantages, and goals. We select and introduce IA-MAC because it outperforms IEEE 802.15.4 and A-MAC, and presents a good mechanism for thermal-awareness. TARA is selected to be introduced as it is the first protocol that has considered temperature as a routing metric in BANs, although solving the problem of high temperature to a small extent. The reason for selecting LTRT is that it is a hybrid of LTR and SHR, and outperforms LTR and ALTR. Finally, since TSHR has lower temperature rise compared to SHR and HPR, its packet drop is nearly zero, and has a long lifetime, it deserves consideration.

IA-MAC Protocol presents improved adaptive medium access control protocol. In addition to the adaptive guard band assignment technique, this protocol has an improved adaptive sleep/wakeup mechanism. Here, channel accesses are performed depending on temperature measurements.

Synchronization mechanism is proposed for collision-free communication. Since this protocol deals with temperature, it fits into the 'Thermal-Aware' category; it also considers medium access, which makes it qualified to be included in the 'Medium Access Control' category. Figure 16 shows how the coordinator and nodes access the channel depending on temperature. A comparison between IA-MAC and A-MAC is given in Table 8.

In the Least Total-Route-Temperature (LTRT) protocol, nodes' temperatures are converted into graph weights and minimum temperature routes are obtained. Since LTR and ALTR algorithms choose the minimum temperature for

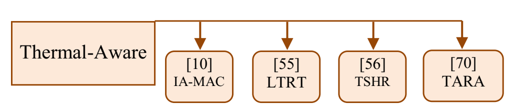


Fig. 15 Selected protocols from the 'Thermal-Aware' category

Table 7 Comparison of the selected protocols from the 'Thermal-Aware' category

Protocol	Goals	Advantages	Disadvantages
IA-MAC	Improving medium access control; achieving adaptive sleep/wakeup mechanism	Has low energy consumption cost, better network lifetime, low packet loss rate	Has lower packet transmission rate at low cycle count
LTRT	Reducing the temperature rise of the implanted sensor nodes in the human body	Provides lower average temperature rise; has the advantages of both SHR and LRT; has lower average hop count	—
TSHR	Efficient thermal-aware routing	Decreases the temperature of nodes; prevents the formation of hotspot; yields lower temperature, zero packet drop, and long network lifetime	Has higher packet delivery rate than HPR and SHR
TARA	Avoiding hotspots during packet transmission	Offers lower maximum temperature rise compared to the shortest hop method; has the ability to balance temperature	Has high packet delay compared to the shortest hop method; has short network lifetime

sending packets to neighbor nodes, the number of hops and the total temperature of the entire network become large. This is because these algorithms are not designed to send packets toward destination nodes. Therefore, LTRT has been proposed to overcome this problem. This protocol is designed to not only choose routes that have the least temperature from sender nodes to destination nodes, but also to avoid wasting the network bandwidth through reducing the hop count.

Fig. 16 Channel access [10]

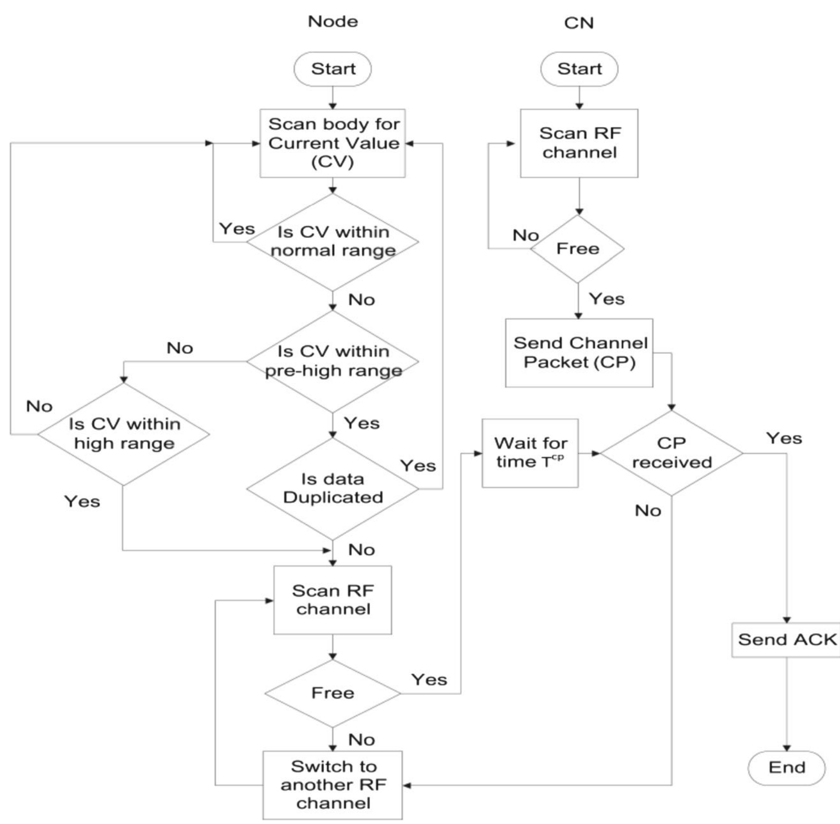


Table 8 Qualitative comparison of protocols

Protocol	Energy consumption	Packet delivery ratio	Number of packet drops	Network lifetime
IA-MAC	Good	Intermediate	Good	Good
A-MAC	Intermediate	Good	Intermediate	Intermediate

Table 9 Comparison of protocols

Protocol	Releasing mechanism	Delay	Energy consumption	Temperature rise	Packet delivery rate
LTRT	Yes	Low	Low	Low	High
TSHR	No	Intermediate	Low	Low	High
TARA	No	High	High	High	Low

LTRT is positioned between LTR and SHR, and is more efficient than ALTR. Just like LTR, ALTR, and TARA, LTRT requires every node to assure the temperature of its neighboring nodes.

This protocol concerns both the shortest hop count and the least temperature rise of the entire network, and is a hybrid of SHR and LTR. This algorithm is based on the single source shortest path (SSSP) in the graph theory, and involves transferring the temperature of sensor nodes to weight so that the SSSP can choose a route where the sum of the temperatures of forwarding nodes is the least [55].

The TSHR Protocol, which has been presented for the application where there is a high priority for delivering a packet to the destination and the packet, is retransmitted if it is dropped. This algorithm has two phases: 1) setup phase, where each node builds its routing table, and 2) routing phase, where the nodes try to route packets through the shortest path. In order to control the temperature of the nodes, two thresholds are defined, one of which is fixed for all nodes and determines a predefined temperature that the node does not exceed; and the other one is a dynamic threshold being set based on the temperature of the node's neighbors and that of the node itself. If the temperature of a neighbor is greater than the dynamic threshold, this means the neighbor is a hotspot. The pseudo code of TSHR procedure has also been provided. Simulation has been run for two types of topology. The results of each type of topology are similar to those obtained from the other type. This protocol helps to reduce the temperature of the nodes, and prevents the formation of hotspot. In high packet arrival rate, the packet delivery delay for TSHR is greater than HPR and SHR, but it has lower temperature. The packet drop in TSHR is zero, and it has a long lifetime [56].

Thermal-aware Routing Algorithm (TARA) is the first protocol introduced with temperature as a routing protocol metric. In this protocol, antenna radiation and power dissipation of node circuitry are considered as two major sources of heat.

The adopted strategy by this protocol is known as the withdrawal strategy. This protocol has a lower temperature rise than the shortest hop routing protocol. The packet roams inside the network for some considerable amount of time, causing high delay and low network lifetime. Yet, the advantage of this protocol is that it balances the load in the network, resulting in reduced congestion and a lower packet drop rate. This strategy avoids the hotspot [70, 71]. Table 9 provides a comparison of TARA with other protocols.

Restriction of location and number of relays protocols

Given that employing multi-hop mode for data transmission results in reducing energy consumption, and thus in saving power consumption and avoiding damage to body tissues, it would be helpful to deploy relaying nodes in body area networks. However, it should be noted that determining relay location is effective in increasing packet delivery rate, and also in reducing packet drops. Furthermore, the number of deployed relays affects cost and energy. Thus, a category concerning restrictive protocols of the number and location of relays has been included in the general classification of protocols.

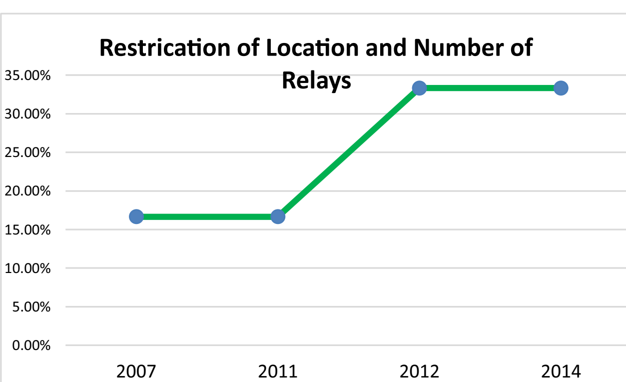


Fig. 17 Percentage of the papers in Restriction of Number and Location of Relays category released in separate years

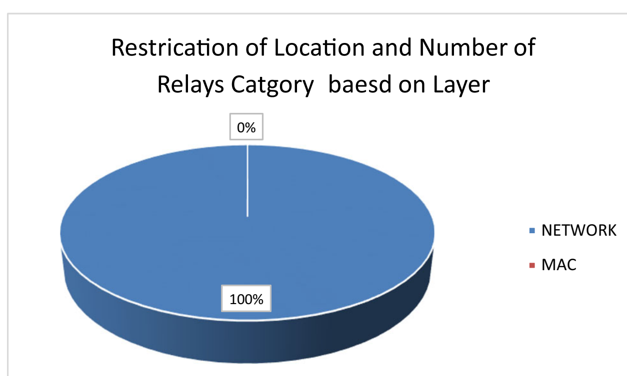


Fig. 18 Breakdown of Restriction of Number and Location of Relays papers in terms of layering

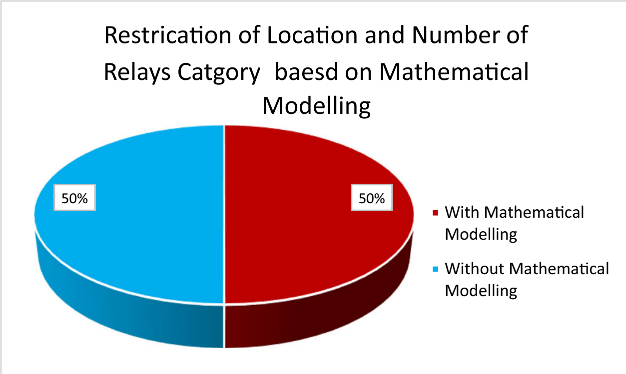


Fig. 19 Breakdown of Restriction of Number and Location of Relays papers in terms of mathematical models deployment

A line graph is shown in Fig. 17 that indicates the years when the papers in Restriction of Number and Location of Relays category were published. 34 % of the papers in this category were published in each of the years 2012 and 2014. Besides, the papers in Restriction of Number and Location of Relays category are broken down in Fig. 18 by layer (network layer and medium access control layer). Figure 19 demonstrates the status of mathematical models deployment in Restriction of Number and Location of Relays category.

References [32, 58, 59], which have given consideration to this field, are introduced in this section as selections from the 'Restriction of location and number of relay' category (Fig. 20). The selected protocols are compared in Table 10 in terms of their advantages, disadvantages, and goals. REEC has been selected because it considers the presence of two relays, expressed by other papers as an abundance of relay nodes, in the network. The reason for selecting EAWD is that

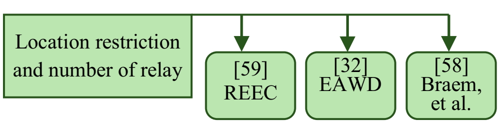


Fig. 20 Selected protocols from the 'Restriction of location and number of relay' category

the number and location of relay nodes have been carefully explored in this protocol. The proposed protocol in reference [58], which could be a guide for relay placement, is introduced due to investigating relay location with regard to single-hop and multi-hop topologies.

Reliable Energy-Efficient Critical data routing protocol in body area networks, also known as REEC. Two intermediate forwarder nodes are used to reduce the communication distance between nodes and the sink, with the source nodes sending only critical data to the intermediate forwarder nodes as the major mechanism.

Results demonstrate that REEC performed better than SIMPLE and M-ATTEMP [59]. Table 11 provides a comparison between the proposed protocol and other protocols.

EAWD Protocol discusses the optimal design of wireless body area networks by investigating the joint data routing and relay positioning problem, in order to increase the network lifetime. The main idea of this protocol is a follows: some locations are considered for each relay node, and also the number of relays that can exist in the network is examined. This is why the EAWD protocol has been included in the 'Restriction of location and number of relay' category. Because of having different transmission power, this protocol also fits into the 'Link-aware' category.

Sensors can reduce their transmission powers to the minimum level necessary to maintain network connectivity, thus protecting human tissue and decreasing energy consumption [32].

Braem and et al. has considered a new communications in terms of energy efficiency [58]. That is, the energy consumption or network lifetime of a single-hop network and a multi-hop network are analyzed. Conducting investigations into the number of relays, this protocol has been included in the 'Restriction of location and number of relay' category. This method also uses the residual energy of each node as a metric, so it comes into the 'Thermal-aware' category.

This method improves the network lifetime. Yet, the problem is that it is not always feasible to use relay nodes. It also

Table 10 Comparison of the selected protocols from the 'Restriction of location and number of relay' category.

Protocol	Goal(s)	Advantages	Disadvantages
REEC	Reliable energy-efficient critical data routing	Has better stability period, network lifetime, throughput, and energy consumption	—
EAWD	Optimal design of BANs through relay positioning in order to increase the network lifetime	Reduces the energy consumed by each node; does not need to install additional relays; offers better mobility by relay positioning	—
[58]	Energy efficiency of communication despite path loss	Increases network lifetime	There is not the possibility of the continuous use of relays, so the cooperation technique has been proposed instead.

Table 11 Qualitative comparison of protocols

Protocol	Residual energy	Network lifetime	Stability period	Throughput
REEC	Good	Good	Good	Good
SIMPLE	Poor	Intermediate	Intermediate	Intermediate
M-ATTEMPT	Intermediate	Intermediate	Poor	Poor

offers lower energy consumption as compared to the case when using relay devices; furthermore, the network lifetime can be improved without the addition of extra devices for relaying. In fact, these methods lead to energy saving and the reduction of path loss [58].

Link-aware protocols

This category has been defined as the link state is of considerable significance in the connections between nodes. It takes into account the factors that affect data transmission and reception, including received signal strength, packet delivery ratio, HELLO messages to ensure connectivity between nodes, and data transmission power. By using protocols which take these metrics into consideration when routing data, better data transmission and reception could be accomplished, which would definitely be effective in the body area network.

A line graph is presented in Fig. 21 that indicates the years when the papers in Link-Aware category were published. As seen in Fig. 21, 19% of the papers in this category were published in 2014. In addition, a breakdown of the papers in Link-Aware category by layer (network layer and medium access control layer) is given in Fig. 22, where 87 % of the investigated papers related to the network layer, and 13 % of them focused on the medium access control layer. Fig. 23 depicts the status of mathematical models deployment in Link-Aware category.

As shown in Fig. 24, references [5, 6, 32, 33, 50, 51, 58, 72] are introduced in this section as selections from the 'Link-aware' category. The selected protocols are compared in Table 12 in terms of their advantages, disadvantages, and goals. IM-simple protocol has been selected because of choosing the next path and node, by an objective function. The reason for selecting CO-lAEEBA is that it provides a cooperative strategy, and also offers higher reliability and performance than other methods. AMR adopts shortest path, received signal strength, and residual energy as routing metrics, and therefore falls into the 'Link-aware' category. Moreover, it uses fuzzy logic to combine the three metrics, resulting in a considerable improvement. Reference [5] is introduced because it examines different transmission powers, and proposes methods for retransmission and hop counts. Since EAWD proposes accurate distance-based energy consumption models, and evaluates the effect of the number and location of relays in the link and energy consumption, it is considered very important and deserves a mention here. Because of examining the link as well as considering deterministic conditions for peer discovery in a communication, EPR has been included in this category.

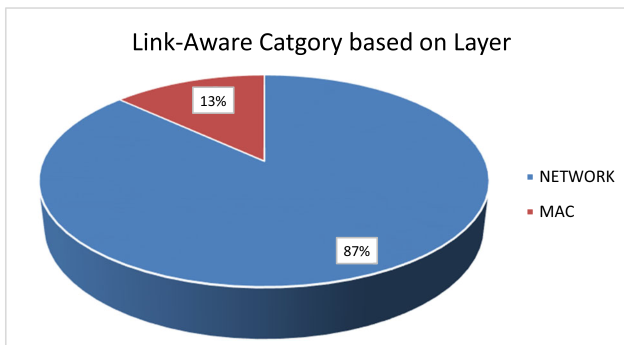


Fig. 22 Breakdown of Link-Aware papers in terms of layering

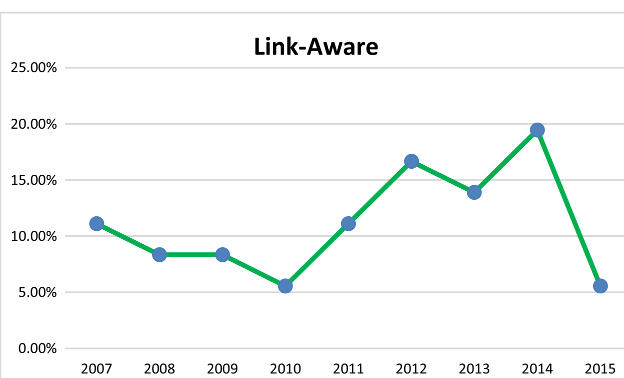


Fig. 21 Percentage of the papers in Link-Aware category released in separate years

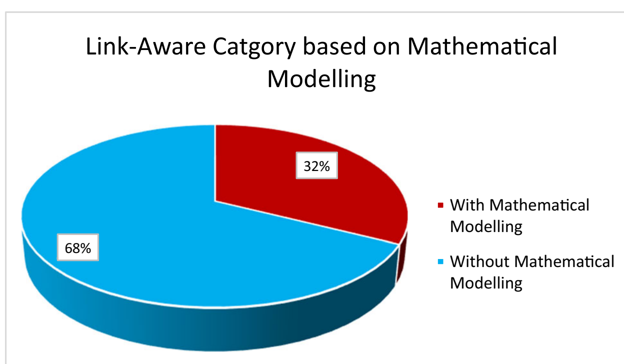


Fig. 23 Breakdown of Link-Aware papers in terms of mathematical models deployment

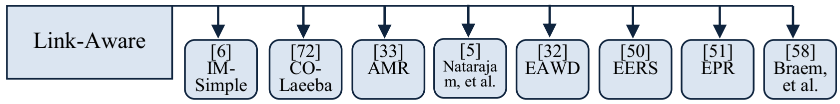


Fig. 24 Selected protocols from the 'Link-aware' category

Reference [58] introduces two mechanisms, i.e. relaying and cooperation, which make it qualified for inclusion in the 'Link-aware' category. These two mechanisms lead to improved link state and thus reduced energy consumption.

Co-LAEEBA Protocol used collaborative learning, where nodes share each others' resources to communicate effectively in terms of successfully received packets. It has been stated that the destination node can combine the received signals by using traditional combining methods such as Fixed Ratio Combining (FRC). In this paper, a new routing protocol, named Co-LAEEBA, is proposed that is an extension of LAEEBA protocol. The proposed model guarantees higher throughput by finding cooperative nodes through the shortest-path routing algorithm. A mathematical model is also presented in this paper which is based on a linear three-node arrangement in which Amplify-and-Forward (AF) technique is employed at the relay and FRC is utilized at the sink. In fact, Co-LAEEBA improves the achieved throughput by LAEEBA. In this method, a route with the minimum hop count is selected for data transmission, which is the reason

Table 12 Investigation of the selected protocols from the 'Link-aware' category

Protocol	Goal(s)	Advantages	Disadvantages
IM-SIMPLE	Reducing energy consumption	Has better stability period, network lifetime, throughput, and energy consumption	Has high packet drop
CO-LAEEBA	Providing a link-aware and energy-efficient protocol	Has better stability period, network lifetime, throughput, and residual energy; has low path loss	—
AMR	Adaptive multi-hop tree-based routing; improving network performance	Uses fuzzy logic, leading to long network lifetime, increased packet delivery rate, decreased data loss, and higher residual energy	Requires additional packet switching between nodes
[5]	Efficient communication between sensor nodes	The multi-hop-PDR network has high packet delivery ratio. The Multi-hop-retransmission network results in high network lifetime, reduced delay, minimal energy consumption, and lower overhead.	The multi-hop-PDR network has delay and high energy consumption. 4-hop or 5-hop networks impose high overhead.
EAWD	Optimal design of BANs through adjusted relay positioning in order to increase the network lifetime	Reduces the energy consumed by each node; does not need to install additional relays; offers better mobility by relay positioning	—
EERS	Achieving Higher reliability and energy efficiency	Has high network lifetime, lower energy consumption, and low delay	Has high overhead in adaptive transmission power
EPR	Presenting a novel architecture for indoor hospital environments, and a new mechanism of peer discovery	Has lower average traffic load; increases the number of successfully received packets; reduces the network traffic; has no buffer overflow	Is likely to increase overhead due to the excessive use of HELLO packets
[58]	Energy-efficient communications despite path loss	Increases network lifetime	There is not the possibility of the continuous use of relays, so the cooperation technique has been proposed instead.

Table 13 Qualitative comparison of protocols

Protocol	Throughput	Residual energy	Stability period	Path loss	Network lifetime
CO-LAEEBA	Very Good	Good	Very Good	Good	Very Good
LAEEBA	Intermediate	Very Good	Intermediate	Poor	Very Good
SIMPLE	Poor	Poor	Good	Very Good	Good
M-ATTEMPT	Good	Intermediate	Poor	Intermediate	Intermediate

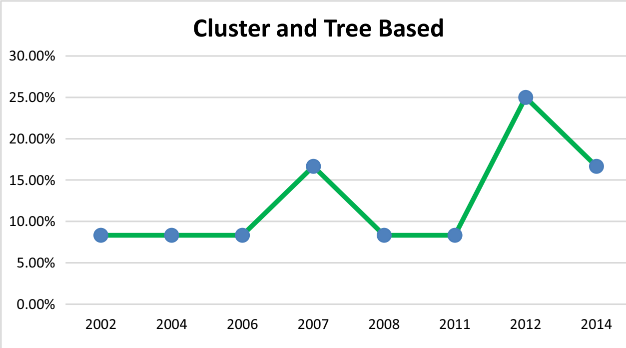


Fig. 25 Percentage of the papers in Cluster-Tree-Based category released in separate years

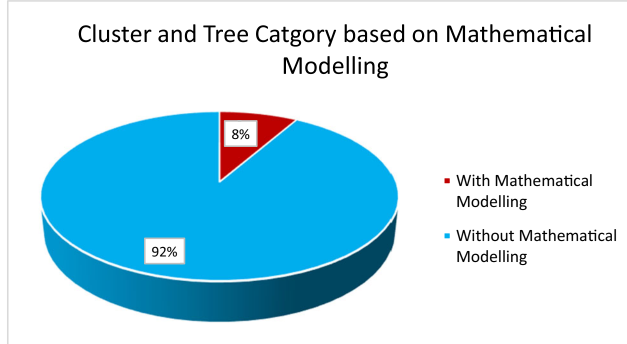


Fig. 27 Breakdown of Cluster-Tree-Based papers in terms of mathematical models deployment

for its inclusion in the 'Link-aware' category. Co-LAEEBA yields better results in terms of stability period, residual energy, and path loss. It also has better throughput as compared to LAEEBA, SIMPLE, and M-Attempt [72]. A comparison between the proposed protocol and other protocols is presented in Table 13.

AMR Protocol presents the adaptive multi-hop tree-based routing protocol, where fuzzy logic is proposed to evaluate several node and network parameters in order to improve network performance in terms of throughput and energy consumption. In this case, fuzzy logic is used to combine three different routing metrics, including hop count, received signal strength indicator (RSSI), and residual energy. The operation of AMR can be divided into two phases, considering nodes inside and outside the sink coverage. Since this protocol uses a combination of parameters such as received signal strength and residual energy, it fits into the 'Link-aware' category. It also comes into the 'Cluster- and Tree-based' category due to making use of tree. This paper evaluates network lifetime, packet delivery ratio, nodes' residual energy, and the number of transmissions per delivered data packet. Fuzzy logic is able to better balance the network load, achieving longer network lifetime than the other metrics [33].

'To Hop or Not To Hop' Protocol has been considered in reference [5]. Two methods are presented in the current work.

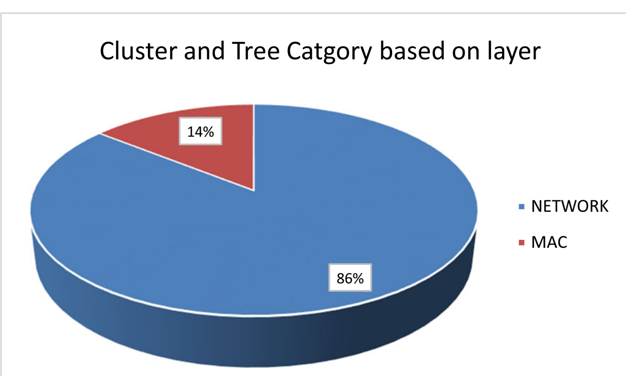


Fig. 26 Breakdown of Cluster-Tree-Basedpapers in terms of layering

A multi-hop network is used because it decreases retransmissions and has higher network lifetime, causing lower delay and energy consumption. The multi-hop network provides robustness to adverse environmental conditions, but it requires overcoming complexity. Among the several possible network configurations of multi-hop architecture, the following two networks are chosen in this paper: (1) a network that performs data routing by maximizing the end-to-end packet delivery ratio, and (2) a network with data routing that minimizes the end-to-end average number of retransmissions. The multi-hop-retransmission network has several advantages; it uses the least amount of energy per packet, increases the network lifetime, and reduces delay; finally, since there are fewer hops, the complexity and overheads are kept low [5]. Since this method discusses the transmission power in communications, it has been classified under the 'Link-aware' category.

Zahoor khan and et al. proposed body area network peering framework, Zahoor Khan or ZK-BAN, and Energy-aware Peering Routing Protocol (EPR) are designed to display in real time body area network data, avoid a fully centralized system, and discover the dedicated BAN data display unit dynamically [51]. The body area network communication in the hospital has two modes: centralized and distributed. In the centralized mode, the body area network connects to the Nursing Station Coordinator (NSC) to get the peering information. In the distributed mode, however, the peer is discovered and data is exchanged. Both distributed and centralized approaches are used in the proposed scheme. Only the central computer holds the information of wireless body area networks and display units, helping to improve privacy and better control body area network communication. The body area network data is displayed on the display unit in a distributed manner which reduces traffic load and helps to improve patient mobility. The proposed model in this paper offers a real-

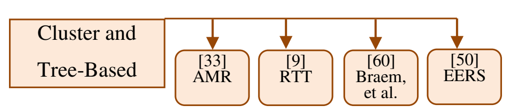


Fig. 28 Selected protocols from the 'Cluster-Tree-Based' category

Table 14 Investigation of the selected protocols from the 'Cluster-Tree-Based' category

Protocol	Goal(s)	Advantages	Disadvantages
AMR	Adaptive multi-hop tree-based routing; and improving network performance	Uses fuzzy logic, leading to long network lifetime, increased packet delivery ratio, decreased path loss, and higher residual energy	Requires additional packet switching between nodes
RTT	Reliable data transfer across the body area network	Has high reliability under slow-fading conditions	Using a large number of relays causes discomfort for the patient.
[60]	Investigating the link in multi-hop mode; and improving CICADA	Increases the number of received packets; and achieves reliability	Causes delay and energy consumption
EERS	Achieving higher reliability and energy efficiency	Has high network lifetime, lower energy consumption, and low delay	Has high overhead in adaptive transmission power

time monitoring system for indoor hospital environments. However, a disadvantage of this method is broadcasting the Hello packets which results in increased network traffic, thereby increasing body area network energy consumption. The proposed protocol has better performance in reducing traffic load, increasing successful transmission rate, reducing the number of forwarded packets by intermediate nodes, avoiding packet drop due to buffer overflow, and reducing overall energy consumption compared to similar protocols [51].

Cluster- and tree-based protocols

This category is introduced because these protocols use tree and cluster for data transmission and reception. This category can be used to avoid packet drop and energy dissipation.

A line graph is given in Fig. 25 that displays the years when the papers in Cluster-Tree-Based category were published. It can be inferred from Fig. 25 that one quarter of the papers in this category were published in 2012. Furthermore, a breakdown of the papers in Cluster-Tree-*Based* category (by layer) is provided in Fig. 26, revealing 86 % and 14 % of the examined papers related to the network layer and the medium access layer, respectively. Figure 27 depicts the status of mathematical models deployment in *Cluster-Tree-Based* category.

As shown in Fig. 28, references [9, 33, 50, 60] are introduced in this section as selections from the 'Cluster-Tree-Based' category. In addition, the selected protocols are analyzed in Table 14 in terms of their advantages, disadvantages, and goals. AMR considers tree by investigating factors like signal strength, residual energy, and shortest path; so this protocol is important and should be mentioned under this category. RTT protocol takes advantage of a tree topology, as an extension of the star topology, which is why it falls into the current category. This protocol allows for relaying with the minimum number of hops. Some schemes have been proposed in reference [60] to improve CICADA; moreover, different powers have been examined in it. It is, therefore, reasonable to introduce the proposed protocol in reference [60] under this category. EERS leads to better performance as it uses CTP, which is a reference protocol, thereby commanding attention. In addition, EERS analyzes transmission powers at different levels, which adds to its significance.

Braem and et al. has proposed a new approach to improve the reliability in body area network [60]. Since this paper presents a technique to enhance the reliability in a body area network, the CICADA multi-hop protocol is used as the base

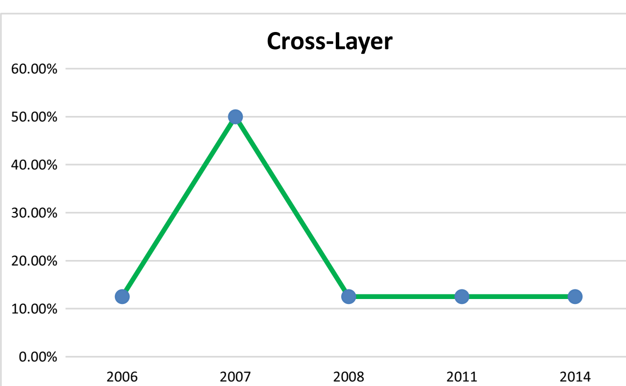


Fig. 29 Percentage of the papers in Cross-Layer category released in separate years

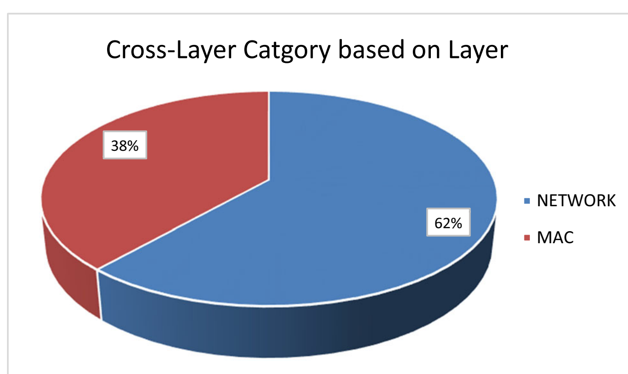


Fig. 30 Breakdown of Cross-Layer papers in terms of layering

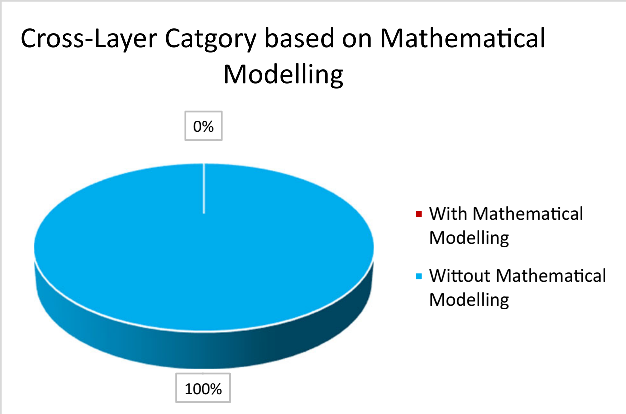


Fig. 31 Breakdown of Cross-Layer papers in terms of mathematical models deployment

protocol. CICADA is a cross-layer protocol that sets up a data gathering tree and offers low delay and high energy efficiency. In this paper, the reliability of CICADA protocol is analyzed, and modifications are proposed to increase the reliability.

Two modifications are proposed to improve CICADA:

1) scheme randomization, and
2) repeating the schemes received from a parent.

The proposed two schemes in this paper increase the number of received packets with little influence on the energy consumption, and enhance the reliability [60].

Cross-layer protocols

This category refers to a combination of medium access control and routing protocols. Since data routing and medium access control are effective in reducing energy consumption and avoiding data collisions, this category has been defined.

The line graph in Fig. 29 indicates the years when the papers in Cross-Layer category were published. The percentage of the papers in this category peaked at 50 % in 2014. Moreover, the papers in Cross-Layer category are broken down in Fig. 30 based upon the layer (network layer or medium access control layer) they related to. 62 % of the investigated papers belonged to the network layer, and the remaining 38 % focused on the medium access control layer. Figure 31 displays the status of mathematical models deployment in *Cross-Layer* category.

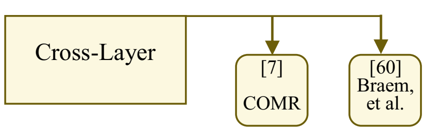


Fig. 32 Selected protocols from the 'Cross-Layer' category

As shown in Fig. 32, references [7, 60] are introduced in this section as selections from the 'Cross-layer' category. In addition, the selected protocols are compared in Table 15 in terms of their advantages, disadvantages, and goals. COMR protocol considers the relay selection mechanism to depend on residual energy and received signal strength; moreover, this cross-layer protocol offers improvements in reliability and energy consumption. Therefore, classifying COMR protocol under this category is fully justified. Reference [60] not only has the advantages of CICDA, including lower delay and energy consumption, but also improves reliability by using a cross-layer design mode. Hence, it appears as one of the selected protocols from the 'Cross-Layer' category.

COMR Protocol is a cross-layer opportunistic MAC/routing protocol that improves the reliability by using a timer-based approach for the relay selection mechanism. The value of this timer depends on Received Signal Strength Indicator (RSSI) and residual energy. The selected relay node will have the highest residual energy and will be closest to the sink as compared to other possible (neighbor) relay nodes. This protocol provides higher energy efficiency than SOR protocol. In this protocol, any node is a sensor node and may also act as a relay node. The handshake mechanism of Request-To-Send/Clear-To-Send followed by data and Acknowledgement are used in this protocol. In this protocol network lifetime increases with increasing the payload size. The transmission radio state consumes less power than the reception or idle listening radio state; as a result, COMR, because of selecting relay nodes with high residual energy, is an improvement on SOR. Packet Delivery Ratio (PDR) decreases with increasing the payload size. End-to-End delay increases due to high payload size. The energy used per bit increases when the payload size is increased [7]. COMR protocol is compared with SOR protocol in Table 16.

Table 15 Investigation of the selected protocols from the 'Cross-Layer' category

Protocol	Goal(s)	Advantages	Disadvantages
COMR	Improving reliability by a cross-layer opportunistic method	Improves network lifetime when the payload size is increased; has lower delay and low energy consumption	Causes packet delivery ratio to decrease when payload size is increased
[60]	Investigating the link in multi-hop mode; and improving CICADA	Increases the number of received packets; and achieves reliability	Causes delay and energy consumption

Table 16 Qualitative comparison of protocols

Protocol	Delay	Network Lifetime	Energy Consumption	
COMR	Good	Good	Good	Good
SOR	Intermediate	Intermediate	Intermediate	Intermediate

Opportunistic protocols

In such protocols, a source node transmits its data toward the neighboring relay nodes, which amplify and forward the data. Thus, it is possible that several relay nodes may receive the data.

A line graph is presented in Fig. 33 that indicates the years when the papers in Opportunistic category were published. According to the graph, 40 % of the papers in this category were issued in 2011. Furthermore, Figure 34 provides a breakdown of the papers in Opportunistic category by layer (network layer and medium access control layer). The status of mathematical models deployment in Opportunistic category is depicted in Fig. 35.

As shown in Fig. 36, references [7, 63] are introduced in this section as selections from the 'Opportunistic' category. In addition, the selected protocols are evaluated in Table 17 in terms of their advantages, disadvantages, and goals. Although there are other opportunistic protocols achieving proper performance, COMR and the proposed protocol in [63] have been included in this category due to evaluating different metrics such as delay, network lifetime, reliability, and energy consumption.

In COMR Protocol, all nodes within the neighborhood of a source node contend for replying to the node, aiming to win access to the channel. Hence, COMR has an opportunistic function, which is why it also falls into the 'Opportunistic' category [7].

Abbasi and et la. proposed a new opportunistic routing protocol in WBAN [63]. Since reliability is a major factor that affects the system performance, interference and inefficient routing can make a body area network unreliable. In fact, an opportunistic routing technique can be a solution to the reliability problem. The use of relay nodes must be optimized in opportunistic routing. An opportunistic routing technique using multiple hops can help to conserve energy and increase the network lifetime. In the opportunistic routing mechanism, a source node transmits its data toward the neighboring nodes, which serve the function of relaying. It is possible that there might be several relay nodes within the coverage of the source node to receive the data. Results depict that using the opportunistic routing can improve parameters like packet delivery ratio, the energy used per data packet, End-To-End delay, and the network lifetime.

Medium access control (MAC) protocols

This category deals with the access to a medium. These protocols, because of making modifications to the frame structure, improve such metrics as energy and delay. It should be noted that energy is the most important reason for defining this category.

The line graph in Fig. 37 shows the years when the papers in Medium Access Control category were published. As seen in Fig. 37, 25 % of the papers in this category were published in 2014. In addition, a breakdown of the papers in Medium Access Control category by layer (network layer and medium access control layer) is given in Fig. 38, where 67 % of the investigated papers related to the network layer, and just under a third were associated with the medium access control layer. Figure 39 shows the status of mathematical models deployment in Medium Access Control category.

As illustrated in Fig. 40, references [6, 10, 33–35] are introduced in this section as selections from the 'Medium Access Control' category. In addition, the selected protocols

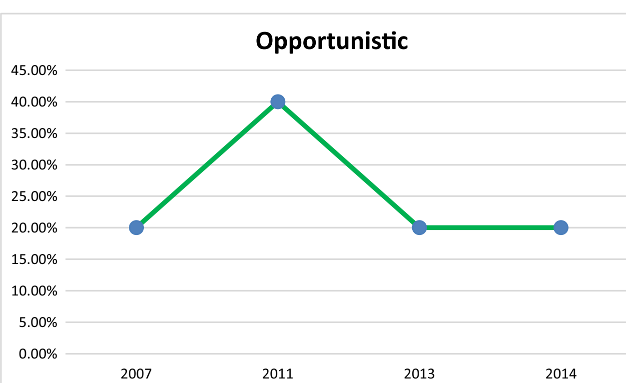


Fig. 33 Percentage of the papers in Opportunistic category released in separate years

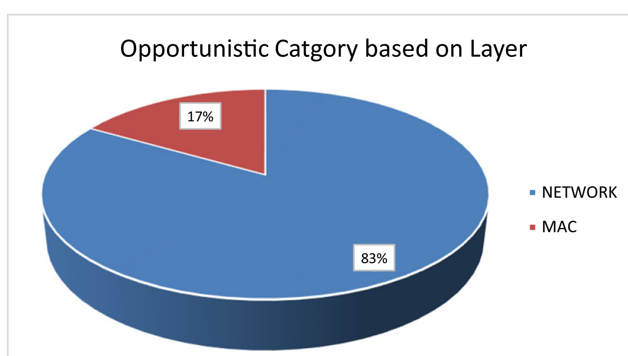


Fig. 34 Breakdown of Opportunistic papers in terms of layering

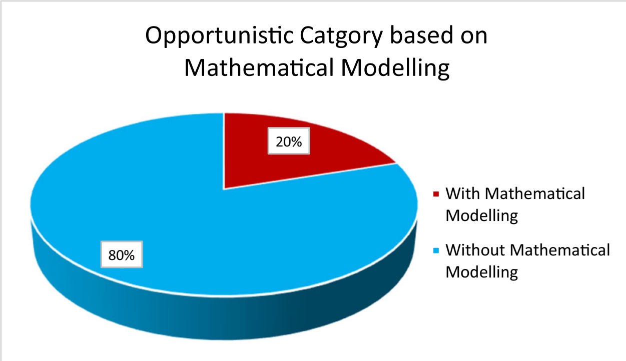


Fig. 35 Breakdown of Opportunistic papers in terms of mathematical models deployment

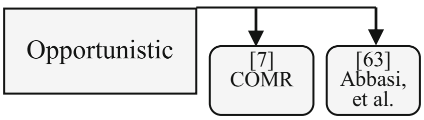


Fig. 36 Selected protocols from the 'Opportunistic' category

are examined in Table 18 in terms of their advantages, disadvantages, and goals. Since IA-MAC is an improvement on A-AMC protocol and extends sleep/wakeup mechanisms, it deserves a mention here. The reason for classifying AMR protocol under this category is that it uses CSMA/CA algorithm whereas other protocols deploy only CSMA. From the 'TDMA' sub-category, IM-SIMPLE is selected because it not only represents an improvement on SIMPLE, M-attempt, and some other protocols, but also produces better results.

Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) are the popular MAC protocols for Wireless Sensor Networks (WSNs) and other short range wireless technologies. Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) are not suitable approaches for medium access in sensor networks because they need complex hardware and high computational power [73]. TDMA approach is well suited for WBANs because almost CSMA/CA is used in dynamic network. However, TDMA based MAC protocols require extra energy consumption for synchronization.

IA-MAC protocol uses medium access control and offers improvements to the sleep/wakeup mechanism, so it fits into

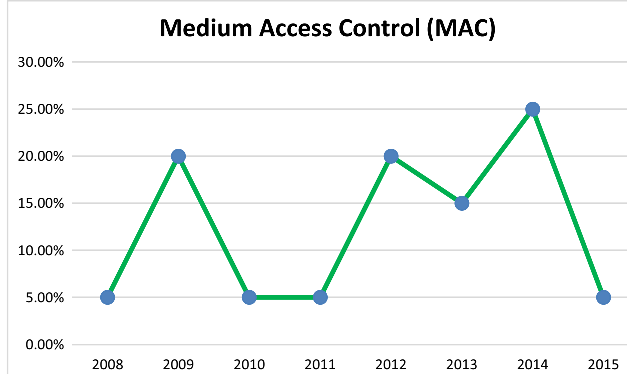


Fig. 37 Percentage of the papers in Medium Access Control category released in separate year

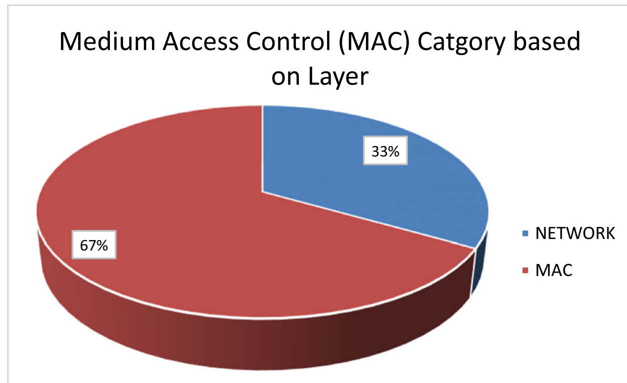


Fig. 38 Breakdown of Medium Access Control papers in terms of layering

the current category. However, this protocol does not refer to a contention-free or a contention-based method; in addition, it is said to use synchronization mechanism to avoid collisions. Thus, it also belongs to the 'MAC' category [10].

The main aim of BODY MAC Protocol is to reduce packet collisions, radio state switching times, idle listening duration, and control packet overhead. The frame structure of this protocol is shown in Fig. 41. In this method, after nodes become synchronized with the sink, they send bandwidth requests to the sink during the contention access period using CSMA/CA. This paper provides a sleep mode mechanism. The main idea for designing the sleep mode in Body MAC comes from the observations that some nodes in a body area network have

Table 17 Investigation of the selected protocols from the 'Opportunistic' category

Protocol	Goal(s)	Advantages	Disadvantages
COMR	Improving reliability by a cross-layer opportunistic method	Improves network lifetime when the payload size is increased; has lower delay and low energy consumption	Causes packet delivery ratio to decrease when payload size is increased
[63]	Using opportunistic routing for achieving reliability	Improves packet delivery ratio, the energy used per data packet, and network lifetime; enhances reliability	LOG NORMAL and the direct transmission method have higher delay

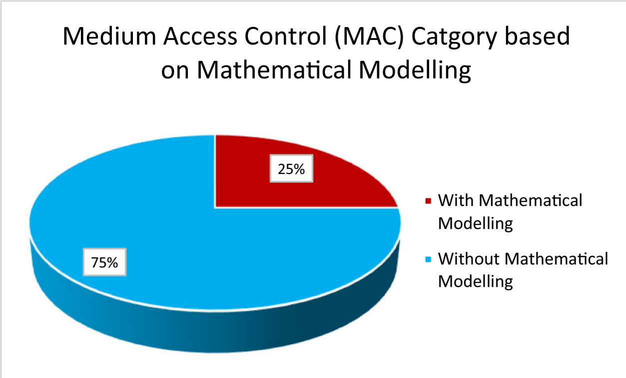


Fig. 39 Breakdown of Medium Access Control papers in terms of mathematical models deployment

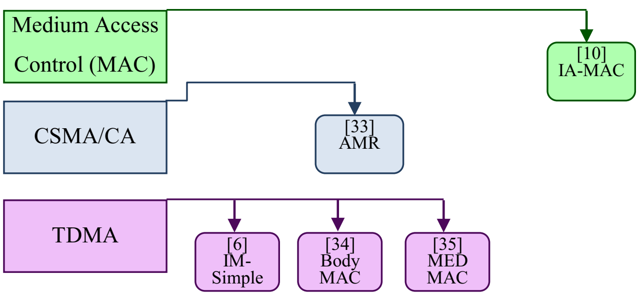


Fig. 40 Selected protocols from the 'MAC' category

very low duty cycles and there are no downlink data or control packets sent from the sink to the nodes. The sleep mode in Body MAC tries to turn off the nodes' radio during beacon, uplink, and downlink. There are three steps involved in the sleep mode procedure: sleep mode request, sleep mode grant, and sleep mode wakeup [34].

Timmons and et al. proposed A medical medium access control (Med MAC) protocol is for energy-efficient and adaptable channel access in body area networks [35]. It is a TDMA-Based MAC protocol for WBANs and employs a novel synchronization mechanism, and initial power efficiency simulations show that the Med MAC protocol outperforms the IEEE 802.15.4 protocol for two classes of medical applications. The main challenge in medical body area networks is to balance the demands of the energy constraint associated with low-power wireless sensor devices, and the quality of service demands. Minimizing transmission and reception operations is a key objective to maximize node lifetime. Therefore, the medium access control (MAC) protocol in a body area network must be highly energy-efficient. The main energy-saving characteristics that must be exhibited by a well-designed MAC protocol are: collision avoidance, overhearing, control packet overhead, receiver idle listening, and transmitter over-emitting. A body area network has to accommodate two types of data which are characteristic of medical services: periodic and non-periodic. Periodic data is traditionally best suited for a TDMA-type protocol, e.g. monitoring temperature and glucose level, whereas non-periodic data is well suited to a contention-style MAC, e.g. medical emergency. The Med MAC solution attempts to provide flexibility, scalability, and adaptability, combined with ultra-low power consumption [35, 74].

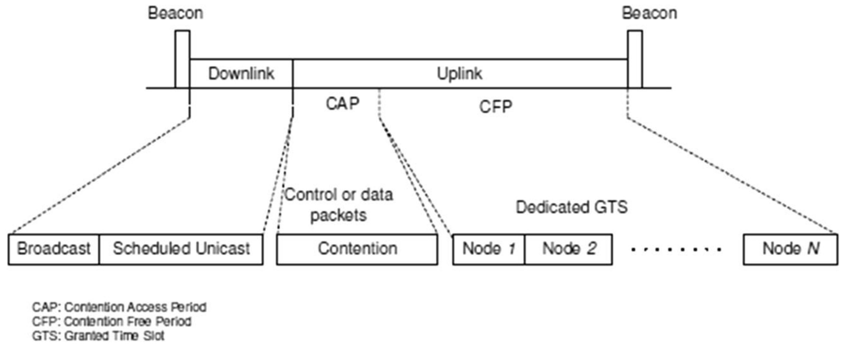
Conclusions and future work

Wireless body area sensor networks, is one of the popular kind of sensor network that used in many applications such as health care, entertainment, gaming, firefighting, and military applications and they have opened up new possibilities. These networks can be both wired and wireless, but considering the convenience and mobility capabilities, wireless networks offer

Table 18 Investigation of the selected protocols from the 'MAC' category

Protocol	Goal(s)	Advantages	Disadvantages
IA-MAC	Improving medium access control, achieving adaptive sleep/wakeup mechanism	Has low energy consumption cost, better network lifetime, smaller packet transmission number, and low packet loss rate	Lower packet transmission rate at low cycle count
AMR	Adaptive multi-hop tree-based routing; improving network performance	Uses fuzzy logic, leading to long network lifetime, increased packet delivery rate, decreased data loss, and higher residual energy	Requires additional packet switching between nodes
IM-SIMPLE	Reducing energy consumption	Has better stability period, network lifetime, throughput, and energy consumption	Has high packet drop
BODY MAC	Presenting a MAC protocol for energy efficiency	The bandwidth allocation flexibility is improved by the dynamic bandwidth allocation mechanism; decreases delay; wastes lesser power consumption	—
MED MAC	Presenting a medical medium access control protocol for energy-efficient and adaptable channel access	Has better power efficiency in low and medium data rate applications; has no synchronization overhead	—

Fig. 41 Body MAC frame structure [34]



more advantages than wired ones. Given the aging of the world's population, the introduction of such technologies will be effective if the proper contexts are provided. These networks consist of some sensors that are placed inside the human body to collect its vital information, which is subsequently transmitted toward the sink or the coordinator node. The sink gathers all the data from the sensors and offers it to users and doctors through network and communication standards.

This paper focuses on wireless body area networks in medicine as well as different aspects of them. Then, the applications of and standards used in these networks were explained. Since precise and timely transmission of data between sensors and the sink is largely dependent upon routing between them, so many protocols have been proposed in this regard. On the other hand, energy consumption is crucially important in WBSNs because of retransmissions, and controlling energy consumption raises enormous challenges. One of the effective energy-saving mechanisms is to perform energy-efficient routing so that energy consumption can be reduced as data is transmitted. Therefore, a classification of current methods pursuing the above-mentioned goal was given. The basis for the proposed classification is how different routing protocols manage energy consumption. Divided into eight separate categories, all protocols were carefully evaluated; then after introducing the goals, advantages, and disadvantages of protocols in each category, a detailed analysis of the evolution of this field was given. It should be noted that 'Restriction of Location and Number of Relays' was the dominant field for studies carried out between 2011 and 2015 on controlling energy consumption in routing, while Link-Aware generally accounted for the largest proportion of all studies between 2000 and 2015. Also as we show there are many hybrid protocols that try to save the energy in different ways. One of the criticisms directed at the idea of controlling energy consumption through routing is that the energy conserved by these methods cannot be further increased beyond the threshold of the involved protocol. As a result, modifying the physical structure of sensors and how data is transmitted and received could be considered a future challenge.

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