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Thermal Aware Routing Protocols for Wireless Body Area Networks: Review and Open Research Issues

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Keywords

Hotspot, Routing protocol, Survey, Thermal-aware, Wireless Body Area Network

REVIEW ARTICLE

Thermal Aware Routing Protocols for Wireless Body Area Networks: Review and Open Research Issues

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Abstract

Wireless Body Area Network (WBAN) is a promising technology that improves life quality and enhances medical healthcare services. The activities and communications of sensors lead to a temperature rise, which can be fatal for the human body. The heating problem is addressed by the thermal-aware strategy, which has great importance. This paper reviews sixteen thermal-aware routing protocols proposed for WBAN; it presents routing in WBAN and its associated challenges. It explains the principles and pros and cons of each protocol and compares the protocols studied using several criteria. Finally, the paper points out the open research issues and challenges. This review intends to provide a comprehensive, up-to-date reference for everyone interested in the thermal-aware communication protocols for WBANs.

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1. Introduction

The last two decades have witnessed the emergence of a new generation of wireless sensor networks called Wireless Body Area Networks (WBANs) [1]. These networks are used in several fields, including military, entertainment, sport, and e-health [2]. WBAN comprises low-power biosensors that can be ported or implanted in the human body. These sensors are used to continuously monitor the physiological state of the human body, such as temperature, blood pressure, and heart rate. The captured data are transmitted to a collector node called *sink* using the radio waves, which forwards them to the external processing center. This radioactivity generates electric and magnetic fields that cause a temperature rise due to the absorption of radiation from the antennas of nodes. Moreover, the electrical consumption of the sensor nodes circuitry during data processing generates heat (by the Joule effect) that intensifies the human body overheating. The temperature rise can be fatal for the person carrying WBAN [3]; a prolonged temperature rise can damage tissue, reduce blood flow in specific organs, and cause enzymatic reactions [4].

The amount of radiation power absorbed by the human tissue per unit of weight is referred to as the Specific Absorption Rate (SAR) [5]. It is measured by the following Equation (1):

$$SAR = \frac{\sigma |E|^2}{\rho} (W / Kg) \tag{1}$$

where σ is the electrical conductivity of the tissue, E is the electric field induced by the radiation, and ρ is the tissue density.

Over the past years, several researchers have tried to overcome the overheating issue. They have proposed many protocols that consider the temperature of sensors as the principal metric in the route selection process. These protocols are called Thermal-Aware Routing Protocols (TARPs) [6]. The primary concern of all TARPs developed for WBANs is to ensure the safe functioning of the network by preventing the temperature of the implanted sensors from rising and promptly decreasing the temperature of the heated ones (hotspots). To this end, data are routed from source to destination away from

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hotspot nodes using the path formed only by cold nodes (Fig. 1).

During the last decade, WBANs have been surveyed from many aspects in the literature. Several studies have been done to clarify the key features of WBANs concerning the network design, implementation issues and challenges, and existing solutions (routing protocols).

Movassaghi et al. [7] presented the use of WBAN in both medical and non-medical fields. The paper provided valuable insights into a variety of routing protocols, security, and technical implementation issues. Cavallari et al. [8] compared and contrasted numerous WBAN technology and design concerns. Khan et al. [9] established WBAN programming frameworks with a particular emphasis on energy-efficient routing protocols. WBANs were the subject of an exhaustive survey by Zuhra et al. [10], which detailed their uses, routing issues, and available solutions. Various routing classes and protocols are covered in this study. Jiang et al. [11] outlined the thermal-aware technology in WBANs. The report studied some existing TARPs and provided a qualitative comparison of the studied protocols. Qu et al. [12] presented WBANs and their classes of routing protocols. The study also provided a comparative analysis of some protocols of each type. Hassan et al. [2] published a comprehensive survey on WBAN. The paper presented WBAN architectures and outlined major WBAN applications and challenges.

Most of these works tried to cover all aspects and classes of routing protocols proposed for WBANs. However, this work deals only with TARPs because temperature rise directly impacts human health and safety. Its purpose is to give an up-to-date review of TARPs focusing on the recent ones. Therefore, an extensive review covering sixteen TARPs with a detailed description of each protocol is provided.

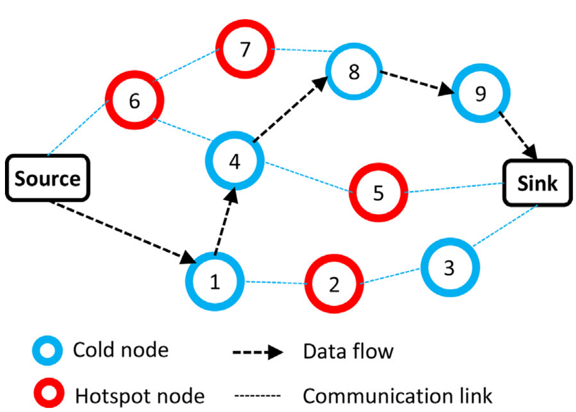

Fig. 1. Routing scheme adopted by TARPs. Data packets are transmitted to the destination using the path that avoids hotspot nodes.

Also, figures illustrating the operating principle, pros and cons, and a comparison of these protocols based on multiple criteria are supplied. Furthermore, open research issues showing the need for more research in this area are given.

The rest of the paper is organized as follows: in section 2, routing in WBANs and its relative challenges are presented. The routing protocols for WBAN are classified in section 3. Section 4 gives a detailed description of the operating principle and the advantages and disadvantages of sixteen TARPs. Section 5 provides the comparative study with a critical analysis of the TARPs studied. Section 6 points out the open research issues and challenges. Finally, this paper ends with a conclusion in section 7.

2. Routing in wireless body area network

The routing protocol is the cornerstone of the communication system of WBAN. It determines the routes used to transmit data packets between the source and the destination nodes. The Intra-BAN communication (Fig. 2) takes place when the sensors transmit the captured data to the central node (sink). This communication is initiated either by a previous request from the sink, a predefined periodic sending, or an alert generated following any failure or exceeding a preset threshold.

The source node can send its data to the sink directly (i.e., one-hop communication); this method provides less delay but consumes more energy. The multi-hop communication can be used to reduce energy consumption, where captured data are sent through intermediate nodes. In such a strategy, the sources can act as intermediate nodes according to their position in the network.

2.1. Routing challenges

WBANs, which are considered a new technology, encounter quite a number of challenges today that they could face in the near future as well. Effective solutions can reduce or resolve some problems, but a few issues are intractable and sometimes context-specific. The subsections below present some challenges that the routing protocols for WBANs must address.

2.1.1. Energy consumption

Energy consumption is a crucial challenge for Wireless Sensor Networks (WSNs) and especially for WBANs. Small batteries generally power biomedical sensors, which need energy for data processing and transmission. The energy required by nodes varies according to the WBAN application.

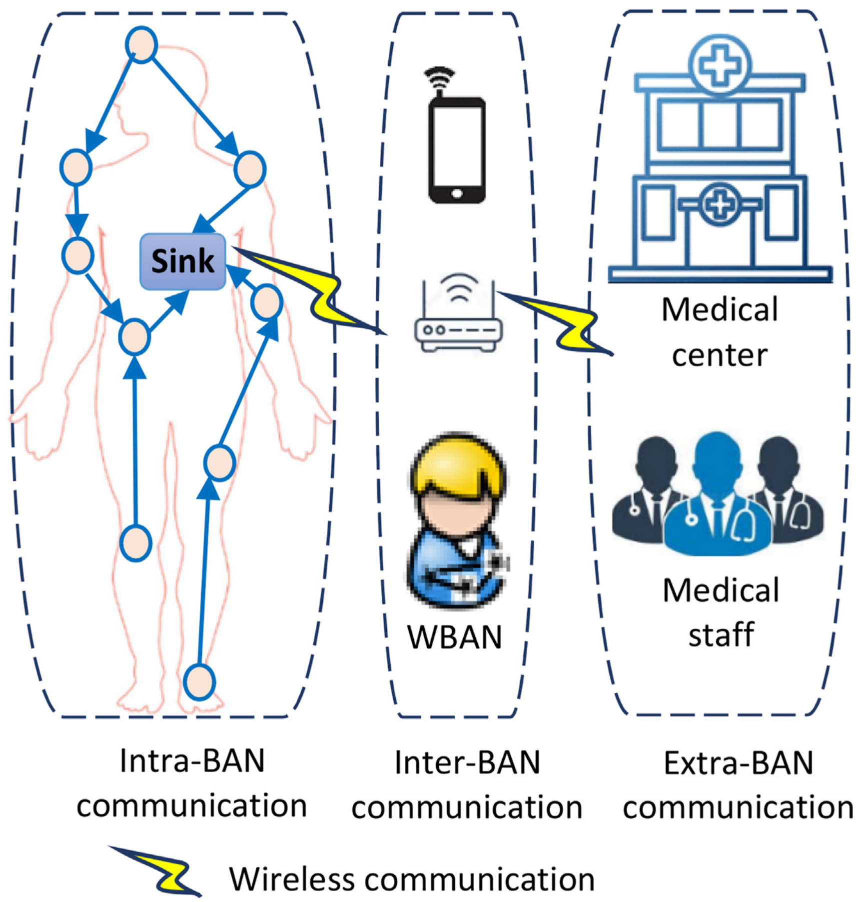

Fig. 2. Communication in WBANs.

All nodes implanted in the human body must function for several years; for example, pacemakers must be used for at least five years [8]. Data transmission is the primary source of energy consumption in WBANs (and WSNs in general); thus, the routing protocol for WBANs must be energy-efficient. It must minimize energy consumption without sacrificing reliability. Furthermore, the routing protocol should ensure equitable participation of WBAN nodes in data transmission to balance energy consumption and reduce breakdowns caused by battery depletion.

2.1.2. Overheating and radiation absorption

The temperature of the WBAN nodes increases during their activities. This rise is due to the activity of the radio transmitter/receiver and the internal circuitry of nodes during data processing. High temperatures can affect the heat-sensitive organs of the human body and can lead to tissue damage [3]. Thus, energy consumption must be limited to a minimum level in order to reduce the temperature rise. Experiments have shown that a high risk of tissue damage can occur when the torso or head tissue is exposed to a SAR of 8 W/kg for 15 min [13]. Therefore, researchers should consider the temperature issue in developing routing protocols for WBANs to avoid overheating and protect the human tissue.

2.1.3. Network lifetime

WBAN lifetime can be defined as the timeframe between the network implementation and its significant damage, which leads to network partitioning with an unreachable destination. As the replacement and recharging of nodes' batteries are not possible, particularly for the implanted nodes, WBAN lifetime is crucial. Thus, a good routing protocol should extend the network lifetime as much as possible.

2.1.4. Body posture

Human body posture is one of the most challenging issues for WBANs [7]. Most of the sensors used in WBAN operate based on line of sight (LoS) communication. LoS propagation can only take place when the sender and the receiver are within sight of each other without any kind of obstacle between them. An absence of LoS can occur when the front and back sides of the human body are used. During sleep, there can be only one side for such communication or no side at all due to the different positions of the body and the use of a pillow or blanket. Thus, signal transmissions could be hampered. Moreover, when the body is seated, the sensors may not communicate properly due to the lack of LoS. Another challenge is body movements; during movement, arms, legs, and the middle of the body can form an angle that prevents communication between sensors. These movements cause frequent changes in the WBAN topology. Therefore, a successful routing protocol must account for these topology changes.

2.1.5. Limitation of the number of hops

According to the IEEE 802.15.6 standard project for WBANs [14], one or two hops communication is authorized in WBANs. The multi-hop transmission provides stronger links that increase the system reliability. However, energy consumption increases proportionally with the number of hops [15]; the higher the number of hops, the higher the energy consumption. However, limiting the number of packet hops has not been considered in most WBAN routing protocols.

2.1.6. Heterogeneity of the environment

WBAN uses different types of biosensors to measure and monitor different parameters of the human body. These biosensors are usually heterogeneous and may also have different capabilities concerning computing power, storage capacity, energy consumption, and transmission power. Thus, a good routing protocol must consider this heterogeneity to improve the overall WBAN performance.

2.1.7. Quality of service

Due to the heterogeneous nature of biosensors used in WBANs, captured data require different quality of service (QoS). The QoS is critical, especially in medical applications, because incorrect or delayed information can have serious consequences, even death [16]. Noncritical data can be sent to the destination with a tolerated delay. However, critical data (e.g., data captured by EEG and ECG) must be sent immediately without any delay or loss; otherwise, they are useless. Therefore, WBAN must have the ability to transmit data in a consistent manner and in real-time. This requirement can be met by an effective routing protocol that guarantees the desired QoS (delay/reliability).

2.1.8. Security and confidentiality

Security ensures the transmission of captured data between the source and the destination securely in a hostile environment [17]. Confidentiality refers to the captured data that can only be accessed or used by an authorized entity [18]. Security and confidentiality are among the basic requirements of WBANs; they are provided by applying conventional security techniques (i.e., encryption). However, these classic techniques are impractical on WBANs given the limitations of their resources, namely computing power, memory capacity, and energy resources. In this regard, developing efficient routing protocols that prevent routing attacks [10] (external attacks or poor sensor behavior) while ensuring data security and confidentiality constitutes a great challenge for developers.

2.1.9. Reliability and fault tolerance

Reliability and fault tolerance for medical WBANs are vital requirements as they directly affect patients' medical monitoring quality. Reliability can be measured by the link quality between network nodes or by the efficiency of the end-to-end communication. Fault tolerance in WBAN refers to the ability of WBAN to restrict the impact of a failure to only a few network components [19]. Undetected life-threatening situations can lead to death. Biosensors are sensitive components to alterations in conditions such as climatic phenomena (e.g., humidity and heat), which can generate errors. Therefore, an efficient routing protocol should detect and remedy these errors to ensure continued data transmission and network functioning.

3. Routing protocols for Wireless Body Area Networks

Numerous works have been completed, and various routing protocols, particularly for WBANs, have been developed to address the previously discussed challenges (section 2.1). These protocols are classified based on their nature and organization into five main categories [12,20] as presented in Fig. 3: (1) QoS-aware, (2) cluster-based, (3) cross-layered, (4) posture-based, and (5) thermal-aware (temperature-aware). Each class of these protocols tries to address a WBAN requirement.

The QoS-aware protocols try to satisfy the QoS requirements. Several QoS requirements must be considered in WBANs [12], namely: data priority, energy efficiency, link reliability, short delivery delay, node temperature, and data security. A QoS-

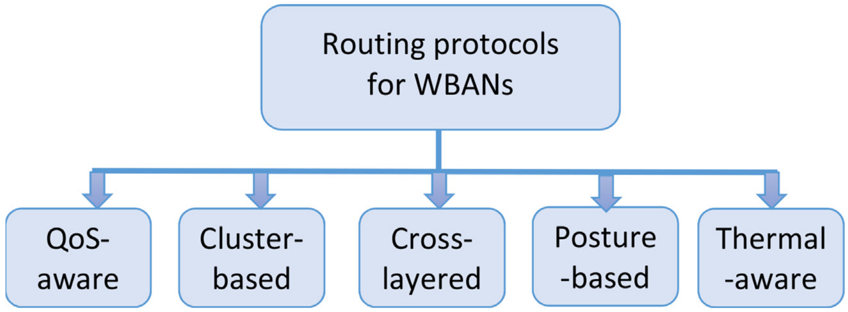

Fig. 3. Taxonomy of routing protocols for WBAN.

aware protocol contains additional modules where each module corresponds to a QoS metric.

In the cluster-based class, WBAN nodes are divided into nonoverlapping clusters. A cluster head (CH) that changes periodically is designed for each cluster. Each node sends its captured data to its CH, which transmits them to the sink. Cluster-based protocols aim to minimize power consumption and maximize network lifetime by avoiding direct transmissions between WBAN nodes and the sink. However, their main shortcomings are the high delays and overheads caused by the periodic CH electing operations.

The Cross-layer protocols use the concept of crossed layers, which allows the different layers of the protocol stack to share state information or co-ordinate their actions. This model can be helpful for WBANs where the network and MAC layers can share information, leading to an improvement in the overall network performance [21].

The posture-based protocols intend to tackle the breaks caused by postural movements of the human body (e.g., movement of limbs), which generate frequent changes in WBAN topology. These protocols aim at reducing transmission times by quickly re-establishing stable links.

The temperature rise of WBAN is mainly caused by the activities of the radio transmitter/receiver of nodes during data exchange and their internal circuitry during data processing. The generated heat is likely to be fatal to the human body carrying WBAN [3,22]. TARPs are developed to overcome the vital thermal dissipation issue. Many researchers have proposed several TARPs that consider the temperature of nodes as the principal routing metric.

4. Thermal aware routing protocols

In the subsections below, various TARPs proposed for WBANs were studied. They are introduced following the chronological order of their apparition, where more attention is attributed to the most recent ones.

4.1. Thermal-aware routing algorithm (TARA)

TARA was proposed in 2005 by Tang et al. [3]; it is the first implementation in this field. TARA identifies nodes with a temperature higher than the threshold level as hotspots. In order to reduce overheating, hotspot nodes are avoided during data transmission (Fig. 4).

In TARA, a node estimates the temperatures of its neighboring nodes by observing their activities; it measures their temperatures by considering their antenna radiation and power dissipation.

TARA implements two phases. The initialization phase aims to create the routing tables where nodes exchange information about their neighborhood concerning the number of hops to the sink. In the routing phase, when a node receives a data packet intended for a hotspot neighbor, it caches the packet for a time period until the temperature of the neighbor drops below the threshold level. This packet is rejected after the expiration of a fixed time period. However, the withdrawal strategy is used if

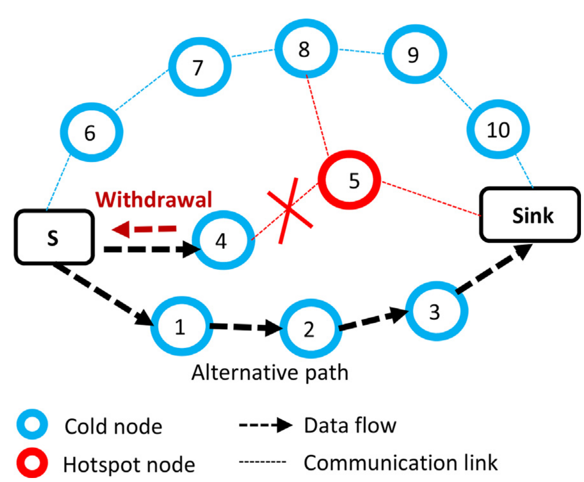

Fig. 4. Operating principle of TARA. When the packet reaches node 4, it estimates the next forwarder (node 5) as a hotspot. Following the withdrawal strategy, the packet is sent back to node S, which finds an alternative route for the packet (1 → 2 → 3 → Sink).

all the neighboring nodes are hotspots (none of them is the destination). The withdrawal strategy, illustrated in Fig. 4, returns the data packet to the sending node in order to find an alternative route. After the cooling of hotspot nodes, they can be considered for later routing.

4.2. Least temperature routing (LTR)

LTR was proposed in 2006 by Bag et al. [23]; it was developed based on TARA. LTR is very similar to TARA, especially in the initialization phase, in which the nodes exchange information concerning their neighborhood; this information is used to build the routing tables. However, the improvement made by LTR lies in the routing phase. In TARA, when a packet arrives at a destination neighbor that is a hotspot, the packet is cached. Nevertheless, in LTR, the packet is sent to the destination immediately, even though it is a hotspot. LTR selects the node with the lowest temperature as the next hop until the destination is reached. However, it cannot guarantee that the packets are routed to the sink through the best possible path.

In LTR, packets count the number of hops passed. If this number exceeds the predetermined value denoted MAX_HOPS, the current packet is rejected and re-routed using an alternative route. This mechanism aims to prevent a packet from going too far into the network. LTR ensures the non-redundancy of the routes by keeping traces (in the packet) of all visited nodes in a fixed time window. Thus, each node tries to forward the packet to the coldest nonvisited neighbor. Fig. 5 illustrates the operating principle of LTR.

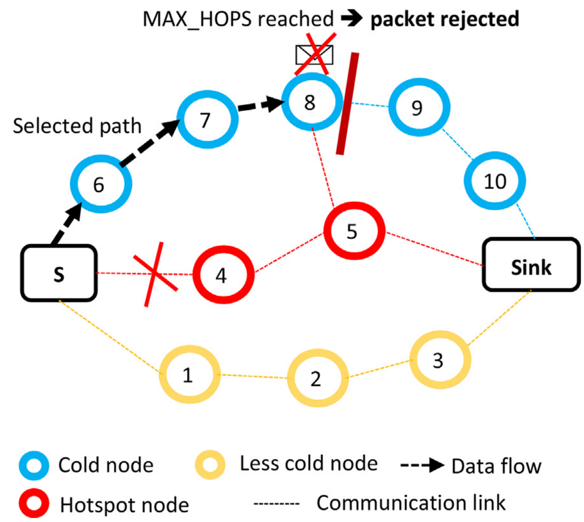

Fig. 5. Operating principle of LTR. When the packet reaches node 8, the hops count exceeds MAX_HOPS; thus, the packet is rejected.

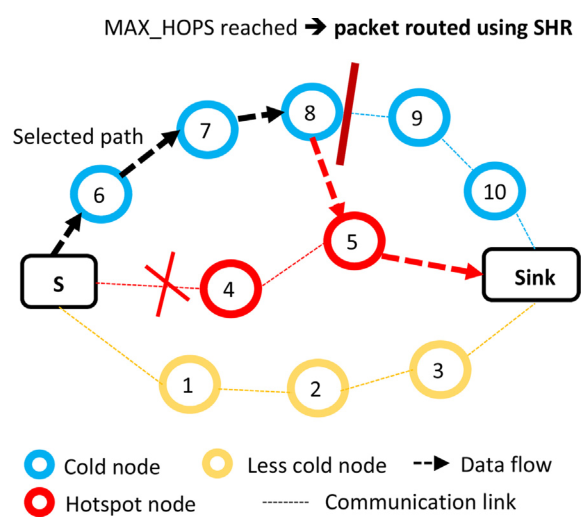

Fig. 6. Operating principle of ALTR. When the packet reaches node 8, the packet hops-count exceeds MAX_HOPS; thus, the packet is routed using SHR.

4.3. Adaptive least temperature routing (ALTR)

ALTR, which is an advanced version of LTR, was proposed in 2006 by Bag et al. [23]. ALTR is very similar to LTR, except it adds a new parameter called MAX_HOPS_ADAPTIVE. When a node receives a packet, it compares the packet-hops-count with MAX_HOPS_ADAPTIVE. If it is smaller than MAX_HOPS_ADAPTIVE, the packet is routed using LTR. When the packet-hops-count exceeds the threshold, ALTR ignores the temperature of nodes and routes the packet using SHR, unlike LTR, which rejects the packet in this case. Thus, the packet can be routed through hotspot nodes. Fig. 6 illustrates the operating principle of ALTR.

The second improvement of ALTR lies in its new mechanism called *proactive delay*, which intends to reduce the temperature rise at the expense of packet delivery delay. When a node having only two outgoing neighbors, which have relatively high temperatures, receives a packet, it waits for a unit of time for the temperature to drop before sending the packet.

4.4. Least total route temperature (LTRT)

LTRT was proposed in 2007 by Takahashi et al. [24]; it is a combination of LTR and SHR. It aims to address the limitations of the previously-discussed protocols (TARA, LTR, and ALTR), which suffer from increased hop counts and network temperatures (because they only consider the temperature of the next hop). LTRT considers the overall temperatures of routes equal to the sum of the temperatures of the nodes forming those routes. It routes packets using the route with the lowest temperature. In order to find the route with the minimum temperature, LTRT converts the network into a graph weighted with temperatures. Then, it applies Dijkstra's algorithm to calculate the shortest path corresponding to the lowest temperature route. The construction of the graph is done as follows: first, each node collects information concerning the temperatures of its neighbors. Secondly, it builds all possible routes to the destination. Finally, it assigns the temperature as a weight to each intermediate node and builds the weighted graph. This operation is repeated periodically to avoid increasing the path temperature because the temperature of the shortest path increases rapidly by using it continually. Fig. 7 shows the operating principle of LTRT.

4.5. Hotspot preventing routing (HPR)

HPR was proposed in 2008 by Bag et al. [4]; it is an improvement of LTR and ALTR. These two protocols tried to reduce the WBAN temperature, but they could not avoid the formation of hotspots. Thus, HPR was developed to prevent the formation of hotspots by using a threshold to control the temperature of nodes. It attempts to reduce the packet delivery delay in order to meet the needs of delay-sensitive applications by preventing packets from taking nonoptimal paths. To this end, HPR transmits packets from sources to destinations using the shortest routes established using SHR.

HPR implements two phases. In the initialization phase, the nodes exchange information concerning their initial temperatures and the shortest paths to the sink. This information is used to build the routing tables. In the routing phase, packets are routed using SHR. If a hotspot node is detected and it is the destination of the packet, then the packet is delivered immediately. Otherwise, the packet is sent to the nonvisited neighbor with the lowest temperature (Fig. 8). In HPR, a hotspot is a node with a temperature higher than the mean of the temperatures of the transmitter and its neighbors, added to the threshold. Like LTR, HPR uses the MAXHOPS threshold parameter to reject packets that exceed this value and a list of recently visited nodes to prevent routing loops.

4.6. Trust and thermal aware routing protocol (TTRP)

TTRP was proposed in 2017 by Bhangwar et al. [25]. It was developed to provide trustworthiness and prevent hotspot formation. TTRP employs additional high-energy relay nodes with the sole purpose of receiving and delivering packets from other nodes. The protocol protects communication from untrustworthy and malfunctioning relay nodes.

TTRP implements three phases: trust estimation, route discovery, and route maintenance. The trust estimation phase controls the reliability of the relay nodes by estimating their buffer. In Fig. 9, each relay node (*Ri* and *Rj*) estimates the buffer of the other relay node to determine whether *Rk* is an untrusted relay node.

The task of the route discovery phase is to find a hotspot-free route that ensures trustworthiness for data transmission. The last phase is route maintenance, which deals with link failures. It restarts the route discovery phase when a node becomes a

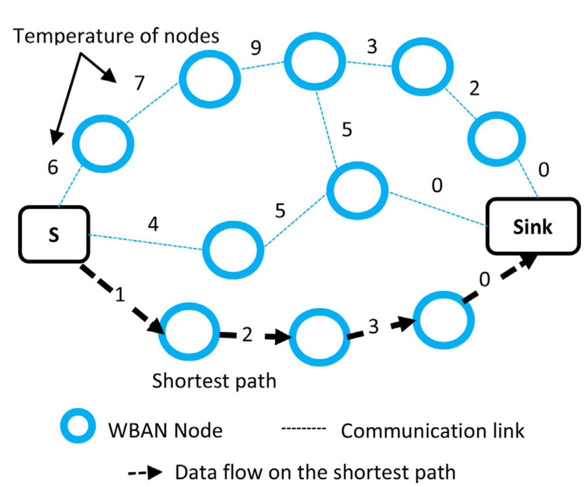

Fig. 7. Operating principle of LTRT. The packet is routed through the lowest temperature path obtained by Dijkstra's algorithm.

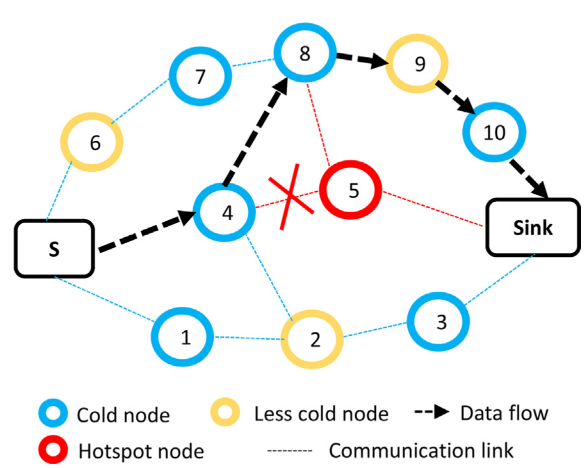

Fig. 8. Operating principle of HPR. The shortest path S→4 → 5→Sink is used to route the data packet. However, when the packet reaches node 4, it estimates the next forwarder (node 5) as hotspot. Thus, node 8 is selected as the next hop because it is colder than node 2.

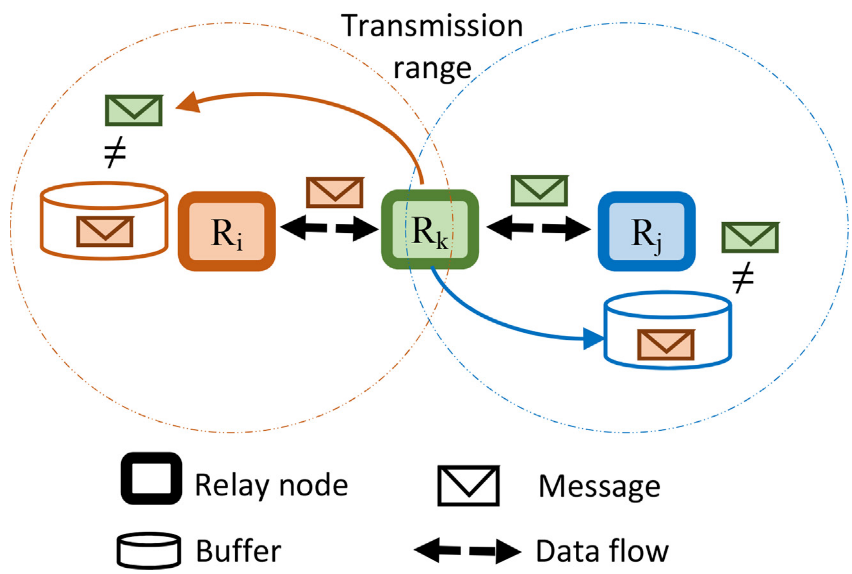

Fig. 9. Estimation of relay node reliability of TTRP. The message sent by Ri is different from the message forwarded by Rk, so Ri and Rj detect this behavior of Rk.

hotspot during communication, or the neighboring node becomes untrustworthy.

4.7. Traffic control thermal-aware routing in body area networks (TRATC)

TRATC was proposed in 2017 by Maymand et al. [26]. It aims to reduce the temperature rise of nodes while controlling the network traffic. For this purpose, TRATC uses two thresholds to control the temperature of nodes and manage network traffic. Firstly, if the temperature of nodes is lower than the first threshold, then the next hop is chosen according to the number of hops to sink and the residual energy. However, if the temperature of a node exceeds the first threshold, then the traffic rate sent to this node is controlled by its neighboring nodes. Secondly, if the traffic flow control is not effective and the node temperature increases beyond the second threshold (i.e., the node becomes a hotspot). Then the traffic is sent to the neighboring node with the second-lowest number of hops to sink (SHR is applied). If many nodes have the same number of hops to the sink, the node with the lowest temperature is chosen. TRATC uses HELLO messages to exchange periodically information about the number of hops to sink, the temperature, and the energy of nodes.

4.8. Mobility-based temperature-aware routing protocol (MTR)

MTR was proposed in 2017 by Kim et al. [27]. It is aimed at supporting the mobility of nodes and preventing temperature rise. Therefore, it reduces the number of packets lost due to the topology changes produced by postural movements of the human body. MTR was developed for delay-tolerant networks by implementing a storage and transport scheme. For this purpose, MTR classifies WBAN nodes based on their position into two classes: static and dynamic. Static nodes refer to nodes in the center of the body, which are unaffected by body movements, whereas dynamic nodes refer to nodes in the moving parts of the body (e.g., arms or legs).

The packets generated by the mobile nodes are routed to the sink as follows: if all links with neighboring nodes are broken, then the node buffers the packets. These buffered packets are transmitted when the link with a neighbor is re-established. However, the routing is similar to LTR for a static node *Ns*, where packets are sent directly to the sink if there are links. Nevertheless, if the lowest temperature of static neighbors is high, then *Ns* tries to route the packet through the dynamic nodes. In fact, for each dynamic neighbor, *Ns* calculates a probability *P* representing its connection quality with the sink. In the case where there is a dynamic node *Nd* with a *P* greater than the threshold, *Nd* is chosen as the forwarder, and the packet is sent to it. Meanwhile, *Ns* triggers a probability-dependent counter *C* used to ensure packet routing during a time period. When all probabilities *P* are less than the threshold or after the expiration of *C* without the packet routing, *Ns* sends the packet to its coldest static neighbor *Nc*. Then the static routing operation re-starts for *Nc*.

4.9. Temperature-aware routing using secondary sink in wireless body area sensor network (TAR-SS)

TAR-SS was proposed in 2018 by Jain et al. [28]. It was developed to overcome the energy hole problem [29]. The energy hole refers to the fact that the nodes surrounding the sink suffer from increased temperatures and rapid depletion of their energy. These nodes are extensively used to route packets from other nodes having no direct links with the sink (Fig. 10).

To overcome the energy hole problem, TAR-SS introduced the concept of *secondary sink*. First, the main sink detects an energy hole situation by periodically monitoring the temperature and energy of its neighbors. An energy hole situation is detected when the temperature of all its neighbors reaches the threshold. In this situation, TAR-SS launches the election of a secondary sink among the nodes with two-hop to sink. From these nodes, the node with the maximum value of the cost function calculated based on the residual energy and temperature is elected as a secondary sink. Following that, the main sink broadcasts a HELLO message containing the identifier of this new secondary sink to all network nodes. The secondary sink plays the role of the main sink during the energy hole period; it is used to allow the cooling of the neighbors of the main sink (Fig. 10). When the secondary sink becomes a hotspot, it informs the main sink, which launches the election of a new secondary sink.

TAR-SS identifies two classes of packets: urgent and ordinary. Urgent packets are sent immediately to the sink; however, ordinary packets are sent in groups. A node keeps in its buffer the ordinary packets, which are transmitted all at once when the buffer becomes full.

4.10. Adaptive thermal-aware routing protocol (ATAR)

ATAR was proposed in 2019 by Jamil et al. [30]; it attempted to balance the temperature rise between the network nodes. Like TTRP, ATAR uses additional relay nodes equipped with high energy to forward the traffic to the destination. ATAR implements two phases: the initialization phase and the data transmission phase. The initialization phase establishes levels for nodes corresponding to their distance (i.e., number of hops) to the sink. At the end of this phase, each node builds its own routing table containing the routes to the sink with their global temperatures (Fig. 11).

In the data transmission phase, packets are transmitted through the lowest temperature route; the sender broadcasts the data packet containing its level, temperature, and relay node ID. The specified relay node re-broadcasts the packet; however, higher-level nodes retain the ID and temperature of the sender node and then discard the packet. The packet is rejected without any action by other nodes (Fig. 11). This process continues until the sink receives the packet.

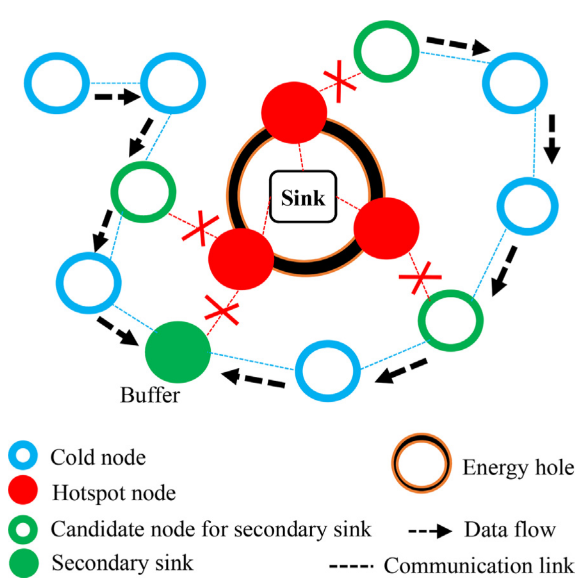

Fig. 10. Operating principle of TAR-SS. When an energy hole occurs, nodes send their data to the secondary sink.

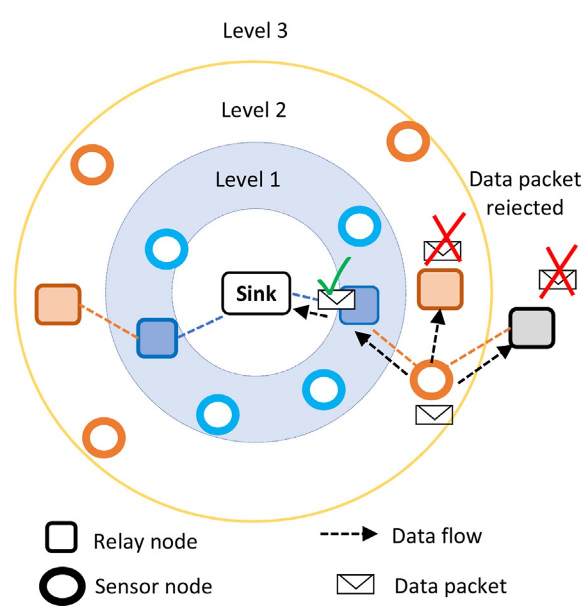

Fig. 11. Operating principle of ATAR. The data sent by a sensor node is received by the relay node with a lower ring level; other nodes discard it.

4.11. Thermal Aware Routing Algorithm for a wireless body area network

Thermal Aware Routing Algorithm for a wireless body area network (TARALG) was proposed in 2019 by Kathe et al. [31]. This protocol manages the priority of packets while avoiding the temperature rise of WBAN nodes.

The protocol implements two phases: in the initialization phase, nodes exchange HELLO messages following the sink initiative. The HELLO message contains the following information: the node identifier, temperature, energy level, and the number of hops to the sink. This information is used for constructing the routing tables. When a node receives a HELLO message from its neighbor, it keeps the containing information in its routing table and deduces its number of hops to the sink. This latter equals the minimum of the number of hops of its neighbors, plus one.

In the routing phase, each packet is marked with a high or low priority depending on the application or the position of the node generating it in the human body (e.g., a sensor on the heart has a high-priority). The packet is sent to the nonhotspot neighbor with the highest value of the objective function *f*. *f* is calculated based on the following four parameters: number of hops to sink, network size, neighbor temperature, and energy. It allows choosing as a forwarder the neighbor having a good distance from the sink, an admissible temperature, and sufficient energy. If all neighbors are hotspots, then the packet is buffered. The oldest packet with the lowest priority is deleted when the buffer becomes full.

In order to manage the priorities of packets, three states (E0, E1, and E2) are defined for each node according to its temperature. First, the protocol uses two thresholds for temperature: *NTemp* and *ThrTemp*, where *NTemp* is less than *ThrTemp*. A node is in state E0 if its temperature is lower than *NTemp*, which means it can transmit high and low-priority packets. It is in state E1 if its temperature is between *NTemp* and *ThrTemp*, which means it can transmit only high-priority packets; for low-priority packets, it buffers them. A node is in the E2 state, which means a hotspot if its temperature is higher than *NTemp*; in this case, the node does not participate in the routing operation (i.e., it enters a cooling phase).

4.12. Thermal aware & energy optimized routing protocol for Wireless Body Area Networks (TAEO-A)

TAEO-A was proposed in 2019 by Javed et al. [32]. It is aimed at reducing the effect of overheating and increasing network reliability. Initially, the nodes exchange information about their identifier, position, temperature, and energy level. Then, the sink diffuses a message to specify its position.

For data transmission, the sink receives data from its surrounding nodes directly. However, multi-hop communication is used for other nodes where the closest neighbor to the sink with the lowest temperature and highest residual energy is selected as a forwarder. Its task is to transmit data from its neighbors to the sink. If the temperature of a forwarder becomes higher than the threshold, then it is deactivated for a fixed period. TAEO-A does not define a constant value for the temperature threshold; its value depends on the position of the sensor in the human body. Therefore, different values can be used for different positions. To save the energy of nodes, TAEO-A determines the energy required to transmit a packet based on the distance between the sender and the receiver nodes. It sends the packet with the lowest power if the distance is less than a specific limit; otherwise, it uses the maximum transmission power. TAEO-A uses the Time Division Multiple Access (TDMA) scheduling scheme where each node sends its data within its time slot. Nevertheless, if it has no data to send, it enters a standby state to save energy.

4.13. High throughput and thermal aware routing protocol (HTTRP)

Bouldjadj et al. [33] proposed HTTRP in 2020, intending to extend the network lifetime and ensure high throughput. HTTRP considers node temperature and residual energy as metrics for routing path selection, in contrast to most other TARPs, which consider the temperature of nodes as the sole metric for routing path selection.

HTTRP comprises two phases; in the initialization phase, nodes exchange information about their temperature, residual energy, and the number of hops to sink. This information is used to create routing tables. In the routing phase, HTTRP identifies two data types: critical and normal. The single-hop strategy is used to transmit critical data where each node elevates its transmission power to send them directly to the sink. However, the multi-hop strategy is used for normal data. In order to save power, the currently captured data are sent to the sink only if they differ from the previously sent data. A sender node chooses its neighbor with the maximum value of the objective function *f* as a forwarder to route the normal data. *f* is calculated based on the temperature and residual energy of nodes. Therefore, the node with high residual energy and low temperature is selected to forward the data. Nodes whose temperatures exceed a threshold are marked as hotspots and cannot be involved in the routing operation (Fig. 12).

When a nonhotspot node receives a data packet, it sends an acknowledgment message (Ack) containing its temperature and energy level to the sender. All nodes that receive this Ack message use its containing information to update their routing tables. However, if the node is a hotspot, it ignores the Ack to save energy and accelerate the cooling operation. After the expiration of the time period *t* triggered by the sender pending the acknowledgment message, the sender assumes a hotspot situation and re-chooses another forwarder.

4.14. Self-heat controlling energy efficient OPOT routing protocol for WBAN

Optimum Path Optimum Temperature (OPOT) routing protocol was proposed in 2020 by Banuselvasaraswathy et al. [34]. This TARP is intended to provide QoS regarding the end-to-end delay, energy consumption, and network lifetime.

OPOT implements two phases; the initialization phase has the task of constructing routing tables. The sink starts this phase by broadcasting a HELLO message containing *hop_count*. WBAN nodes use this HELLO message to exchange information about their temperature, residual energy, and the number of hops from the sink.

In the data transmission phase, nodes send their data directly to the sink if the separating distance is short. Otherwise, multi-hop routing is used. A sender chooses as a relay node from its neighbors the neighbor with the minimum distance to sink, low temperature, and high residual energy.

OPOT identifies two temperature thresholds: *Th_min* and *Th_max.* It recognizes three priorities for packets: *high*, *medium*, and *low*, corresponding to three types of data: *critical*, *abnormal*, and *normal*, respectively. A neighbor with a temperature greater than *Th_max* can only forward high-priority packets; it discards other packets (i.e., medium and low) (Fig. 13). When its temperature drops below *Th_max*, it can be re-solicited again for routing abnormal and normal data.

4.15. An efficient routing protocol for internet of medical things focusing hot spot node problem

ATAR2[1] was proposed in 2021 by Ghufran et al. [35]. It is a thermal-aware protocol aimed at extending network lifetime by judiciously using the energy of nodes. The main idea of ATAR2 resides in the use of adequate transmission power (TP) to send packets from source to destination. Thus, ATAR2 adjusts the required TP according to the value of the received signal strength indicator (RSSI) read from its neighbor (destination).

The minimum TP is used with a maximum RSSI value in order to ensure energy efficiency and reduce heat generation. However, the TP increases

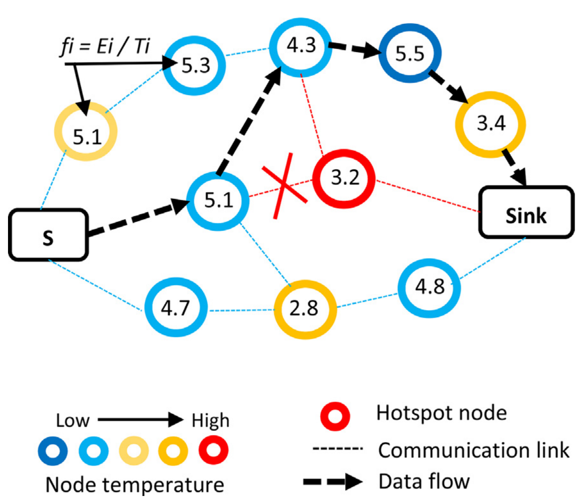

Fig. 12. Operating principle of HTTRP. A node transmits the data packets to its nonhotspot neighbor with the maximum f. If more than one neighbor has the same f, then the neighbor located on the shortest path to the destination is selected.

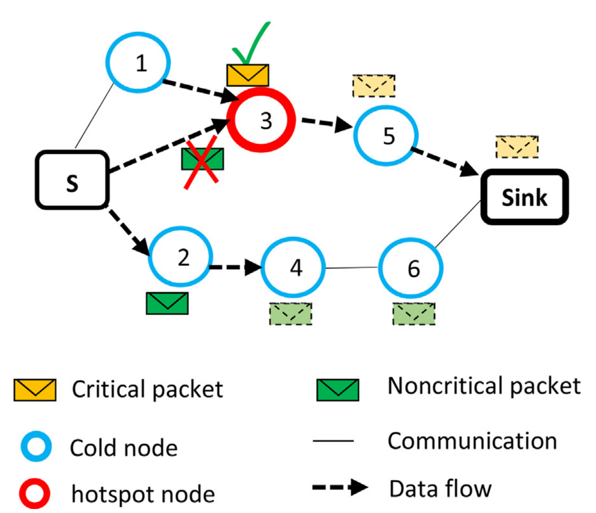

Fig. 13. Operating principle of OPOT. The hotspot node (3) continues to forward critical packets while discarding noncritical packets that are routed through the alternative path (S→2 → 4→6→Sink).

[1] The original name used by the authors is ATAR. The name ATAR2 is used to differentiate it from ATAR discussed in section 4.10.

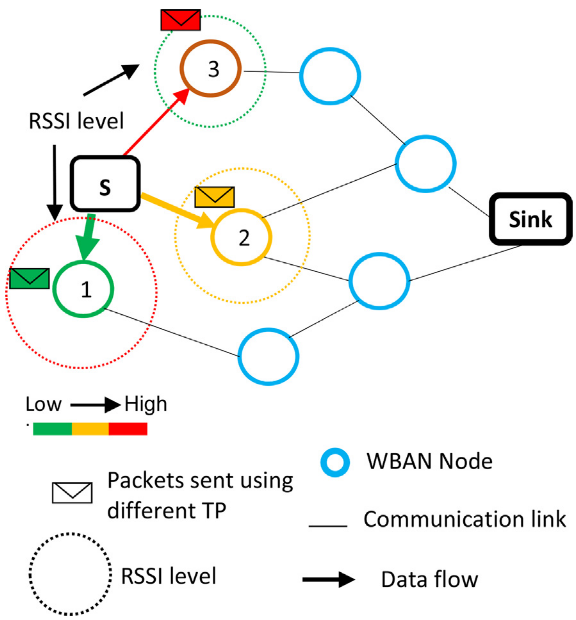

Fig. 14. Operating principle of ATAR2. The transmission power used to transmit a packet to a neighbor depends on its received RSSI. As a result, node (S) sends its packets to its neighbors (1,2,3) using different TPs according to their respective RSSI levels.

inversely with RSSI (i.e., low RSSI needs high TP and vice versa).

ATAR2 defines two thresholds for RSSI: *ThLo* and *ThHi*. These values are used to determine the TP to be used. If RSSI is higher than *ThHi*, the TP is decreased. However, when RSSI is lower than *ThLo*, the TP used would be set a level up (increased by a margin value) to prevent losing data packets. Fig. 14 illustrates the operating principle of ATAR2.

4.16. mobTHE (mobile temperature heterogeneity energy) aware routing protocol for WBAN IoT health application

mobTHE was proposed in 2021 by Selem et al. [36]. This TARP aims to ensure good network performance in terms of throughput and network lifetime while overcoming the disconnection problem. The disconnection is caused by the mobility of the sensors attached to the moving parts of the human body (e.g., arms and limbs). mobTHE stipulates the existence of two sinks playing the role of coordinators (Fig. 15). One-hop communication is used between each sink and node within its transmission range. However, a sensor node may be isolated (i.e., it is out of the coverage of both sinks) due to postural changes. In such a situation, the isolated node should adopt two-hop communication by using a neighboring node as a relay node (parent node). The parent node is the node having the highest link quality among all of its neighbors.

mobTHE comprises two principal phases; in the initialization phase, each sink broadcasts its ID and location in a HELLO message. Once a sensor node

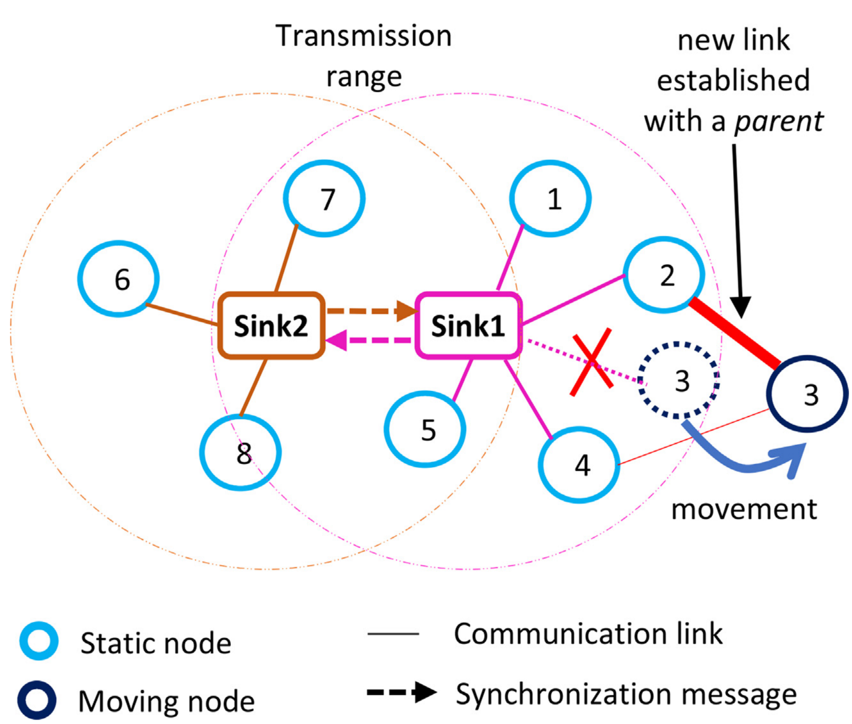

Fig. 15. Operating principle of mobTHE. The moving node (3) selects as parent node among its neighbors (2,4) the node with the strongest signal quality (node 2), which in turn forwards the data packets to the closest sink.

receives this HELLO message, it stores the information (i.e., the ID and location) concerning the closest sink. It then broadcasts a HELLO message containing its ID, energy level, temperature, and location.

In the routing phase, nodes send their critical data directly to the corresponding sink. However, the normal data are sent to the sink only if they are different from the previously sent data to preserve the energy of the nodes.

A moving node periodically broadcasts a HELLO packet to inform other nodes about its new location. In response to it, the two sinks broadcast an Ack packet to ensure the strength of the signal. If the moving node cannot receive the Ack, it sends its data to its parent node, which forwards it to the nearest sink. mobTHE implements a synchronization mechanism between the two sinks to ensure nonredundancy of data, which may be caused by moving nodes (Fig. 15).

5. Comparative study

The primary consideration of all thermal-aware routing protocols designed for WBANs is to minimize the temperature rise of the implanted sensors inside the human body to avoid its harmful effects. However, as discussed in section **2.1**, these protocols must achieve good performance regarding numerous issues and challenges. To this end, state-of-the-art TARPs have adopted several techniques and strategies, which are often context and application-dependent. In what follows, the investigated communication protocols are critically discussed, considering their main features, advantages, and limitations.

TARA is considered the first implementation in the thermal-aware field. TARA achieves significant thermal efficiency in terms of temperature rise compared to SHR. Its withdrawal strategy can increase the rate of delivered packets. However, it increases the number of retransmissions as the previous sender should go back to look for an alternative forwarder after already checking all hotspot nodes. As a result, an energy-draining occurs, and the network lifetime is negatively influenced due to the long routing time.

Both LTR and ALTR tried to address the problems of TARA. LTR attempted to address the TARA shortcomings (namely the high retransmission rate) by implementing a greedy strategy that delivers the packet to the destination even if it is a hotspot. However, LTR provides high end-to-end delay and low reliability because it cannot guarantee that data packets are always directed to the destination. Thus, the packet hops increase, resulting in higher energy consumption.

ALTR tried to address this problem and improve the packet delivery rate by applying SHR after the packet made certain hops. However, it violates the thermal-aware strategy that can significantly increase the temperature of hotspot nodes, leading to fatal consequences. Additionally, the proactive delay adopted by ALTR is helpful in less connected topologies. It may reduce the average temperature of the network, but it can also increase the average packet delivery delay.

LTRT tried to address the average temperature rise of the network compared to LTR and ALTR by employing an end-to-end approach based on Dijkstra's algorithm for route selection. However, calculating all paths and the periodic updates cause high energy consumption, which may affect the delivery delay and the network lifetime. Besides, choosing the shortest path (least temperature path) may not be the best path concerning delivery delay and energy efficiency.

HPR used a bit similar strategy as ALTR; it tried to reduce the max temperature rise of the network. The main difference between HPR and its predecessors lies in its dynamic method used for marking hotspots. Unlike other protocols that use a fixed threshold, HPR calculates the threshold based on the temperatures of the transmitter and its neighbors. HPR routes packets using SHR, but it chooses the coldest neighbor when a hotspot is identified. However, routing using SHR is not ideal for the network lifetime. Also, calculating the threshold value and the packet rejection mechanism used by HPR can reduce the network lifetime.

TTRP is the only protocol that integrates trustiness with thermal awareness. It protects communication from untrustworthy and malfunctioning relay nodes, which are additional high-energy nodes used to receive and deliver packets from other nodes. However, TTRP does not offer any guarantee concerning sensor nodes. Besides, it uses additional control messages that can reduce the network lifetime and increase the end-to-end delay.

The main idea introduced by TRATC is the use of two thresholds to control the temperature of nodes and manage network traffic. It implements a traffic flow control to maintain the temperature of nodes at an acceptable level. However, TRATC periodically exchanges information about the number of hops to sink, the temperature, and the energy of nodes using HELLO messages, which is a costly solution for the WBAN constrained resources.

MTR is among the rare protocols that consider mobility support. It reduces the number of packets lost due to the topology changes produced by the postural movements of the human body by implementing a storage and transport scheme. However, MTR achieved a high end-to-end delay due to the buffering mechanism adopted by dynamic nodes. Thus, it is not suitable for delay-sensitive networks. Besides, for static nodes, routing through moving nodes in hotspot situations can reduce the delivery rate and increase the number of hops. Additionally, calculating the routing probability can negatively influence the energy of nodes and the network lifetime.

TAR-SS is the sole protocol that tries to overcome the energy hole problem by maintaining an acceptable temperature rise in the network. It introduced the idea of *secondary sink*. However, using a sensor node as a sink can create an imbalanced load between WBAN nodes. The secondary sink suffers from a high load, causing fast depletion of its energy, namely in the case of high traffic networks. Furthermore, the delivery time increases proportionally with the network load.

Like TTRP, ATAR uses particular nodes dotted with high energy as relay nodes. However, this additional equipment may annoy the person carrying WBAN. Besides, dividing the network into rings is not a good idea for WBANs because of their reduced size and energy constraints. Moreover, creating and maintaining these levels require additional information exchange concerning levels, temperature, and the number of hops to reach the sink. Thus, this approach incurs much protocol overhead and high energy consumption, which may reduce the network lifetime.

TARALG manages packet priority while preventing temperature rise. Its approach is based on buffering packets when a hotspot is identified. However, the memory of a sensor can quickly become full due to its limited size. In that case, the mechanism applied to free-up sensor memory consists of deleting the oldest packets. Therefore, data loss may occur, which would reduce the packet delivery rate and the WBAN reliability.

TAEO-A has successfully reduced temperature rise, increased throughput, and extended network stability. The main novelty of TAEO-A resides in its multiple temperature thresholds defined for sensors according to their positions on the human body. It also uses two transmission powers according to the distance separating the sender and the receiver nodes. However, defining multiple transmission modes for multiple distances is more energy-efficient. Because it uses the high transmission power to transmit packets to nodes situated a bit farther than the limit distance where it is more adequate to disburse lower transmission power. Besides, TAEO-A ignores data priority, which is very important for patient monitoring applications.

The primary goal of HTTRP was to extend the network lifetime and minimize the formation of hotspots by ensuring that all nodes participated equally in the routing process. HTTRP accomplishes this through a route selection mechanism that diversifies the routing paths. However, because diversifying the routing paths necessitates routing via all potential pathways, packets are not necessarily routed through the best feasible (i.e., optimum) paths. As a result, HTTRP may not ensure the best end-to-end delay and may reduce the packet delivery rate.

ATAR2 tried to extend network lifetime and reduce heat dissipation by adjusting the TP required to transmit a packet. A sender node defines the required TP based on the RSSI level received from its neighbors. This way, ATAR2 reduces energy consumption and heat dissipation. However, it is not clear how ATAR2 establishes the routing paths and how it selects the next forwarder. Moreover, it is unclear how the information concerning temperatures and energy of nodes is exchanged between the WBAN nodes and whether they are used in the route selection process. ATAR2 neglected data priority, and the route selection, as explained in ATAR2, is solely dependent on RSSI levels with no consideration for the temperature or residual energy of nodes. By the way, this may cause an unbalanced load among the WBAN nodes. A node Nr with a high RSSI level is highly solicited by its neighbors in order to reduce their energy consumption. However, Nr may run out quickly and suffer from a temperature rise. The authors just simulated ATAR2 and conducted a comparative analysis with LSE-TPC and MPR. Thus, the efficiency of the proposed solution may not be credible. It would be desirable to do a full simulation (of all three protocols) to be sure of the efficiency of the proposed protocol.

OPOT was successful in lowering temperature rise, increasing throughput, and extending network lifetime. However, some design aspects are not clearly explained in the protocol. Firstly, it is unclear how neighbors' information (i.e., energy and temperature) is exchanged to keep the local information of nodes up-to-date. Secondly, OPOT does not specify what to do if the temperature of a node is between *Th_min* and *Th_max*. Moreover, *Th_min* is pointless because the proposed protocol can function with only one temperature threshold. Finally, OPOT does not specify what to do when a node desires to send a noncritical packet where the temperatures of all its neighbors are greater than *Th_max* (are hotspots). Besides, continuing to send critical data through a hotspot node violates the thermal strategy. All these issues may cause misfunction or blocking situations.

Like MTR, mobTHE is a thermal protocol that considers mobility support, which is crucial for WBAN. It uses two sinks that coordinate between them to ensure data consistency. The simulation shows that it achieves good performance. The efficiency of mobTHE proved for a small network, however, may be reduced with a larger network. More control packets are needed, namely for handling the moving nodes, which can affect the communication quality and cause network congestion. Additionally, the placement of nodes must be carefully considered because the moving nodes can have only one possible parent-node, which can be highly solicited and thus quickly run out.

Table 1 below provides a comparison of the sixteen TARPs previously studied.

6. Open issues

WBANs are one of the most promising technologies that can improve life quality and enhance medical healthcare services. As discussed in section 4, a substantial number of solutions have been proposed to overcome the heating problem and avoid its harmful effect on the human body. However, as summarized in the subsections below, some issues remain insufficiently tackled, which may constrain the wide use of WBANs.

6.1. Energy efficiency

Due to the limited power supply in WBAN, where sensors are powered by difficult-to-replace batteries, particularly for implanted sensors, the network lifetime highly depends on energy management. For that reason, TARPs should consider energy in the route selection process. Unfortunately, among the studied protocols, only a few are energy-friendly. Some of these protocols stipulate the existence of additional nodes acting as relay nodes (TTRP [25] and ATAR [30]). However, others tried to select the next forwarder with the highest energy value. Both strategies have their drawbacks; for the first class that uses relay nodes, in addition to the material overcharge, they may affect people and disrupt their comfort. Otherwise, for the second class, neighboring nodes need to periodically exchange the energy level information to keep their local information up-to-date. Thus, additional messages may be required, which can intensify energy draining.

Energy is vital as well as a scarce resource in WBAN. Thus, applying a good strategy that extends network lifetime by improving energy conservation for all network nodes is a challenging task that requires more investigation. Furthermore, using energy scavenging, which was not treated in this paper, from human body sources [37,38], namely body heat and body vibration, should improve network lifetime considerably and achieve autonomous WBAN.

6.2. Mobility support

The WBAN is composed of nodes deployed on the human body. Because human body movements are persistent, they could cause path loss due to multiple disconnected links and changes in the network topology. Nevertheless, mobility has been given little attention so far. Only MTR [27] and mobTHE [36] have tried to address the mobility issue among the studied TARPs. However, the technique adopted by MTR is inefficient regarding the network lifetime. Besides, the solution used by mobTHE suffers from a drawback: it requires additional control packets, which may cause serious problems for big networks. Therefore, developing solutions that integrate mobility support with thermal-aware strategy is quite hard to achieve in WBANs and constitutes an important research issue.

6.3. Congestion control

In WBAN, data collected by sensors should be sent to the sink using a multi-hop strategy. Therefore, the nodes surrounding the sink are highly solicited and suffer from colossal overload, leading to network congestion and energy-hole formation, which may affect emergency data delivery. The congestion issue has not been addressed considerably; only TAR-SS [28] and TRATC [26] among the studied TARPs attempted to address it. However, they have limitations regarding the delivery delay, energy consumption, and charge balancing. As a result, effective solutions are highly required in this regard.

6.4. Delivery delay

WBAN is typically used for medical care applications. These applications require data delivery without any kind of delay, which can lead to severe consequences and even be fatal. However, there is a contradictory issue here because the thermal-aware

Table 1. *Comparison of the studied thermal-aware routing protocols.*

Ref.	Protocol Year	Objective/ Methodology	Routing depends on	Performance metrics	Compared with/ Simulation tool	Packet rejection	Control messages	Data priority	Mobility support	Relay nodes	Limitation
[3]	TARA 2005	Reduce node over-heating by avoiding hotspots in the routing operation	Temperature of nodes	Maximum and average tempera-ture, delivery delay	SHR/MATLAB						Network overload, reduced network lifetime, high de-livery delay
[23]	LTR 2006	Reduce the amount of heat produced in the network	Temperature of nodes	Average tempera-ture and delay, en-ergy consumption, packets rejected/ delivered, network lifetime	SHR, TARA/C	✓					High delivery delay, network overload
[23]	ALTR 2006	Reduce the amount of heat produced in the network and reduce the delays	The temperature of nodes and the number of hops	Average tempera-ture and delay, en-ergy consumption, packets rejected/ delivered, network lifetime	SHR, TARA/C						High delivery delay, creation of hotspots
[24]	LTRT 2007	Reduce the number of hops and route the packets through the lowest temper-ature route	The total tempera-ture of routes	Average tempera-ture, number of hops of the deliv-ered packets	LTR, ALTR, SHR/ Java		✓				Network overload, creation of hot-spots, reduced network lifetime
[4]	HPR 2008	Avoid the creation of hotspots and reduce the packet delivery delay	Temperature of nodes	Maximum temper-ature of nodes, rejected packet rate, average delivery delay, network lifetime	TARA, SHR/C	✓					Reduced network lifetime
[25]	TTRP 2017	Ensure reliability of nodes and avoid the creation of hotspots	Reliability and temperature of nodes	Average network temperature, throughput, average end-to-end delay, percentage of dropped packets	TARA, HPR/NS2	✓	✓	✓		✓	High end-to-end delay
[26]	TRATC 2017	Control the network traffic to avoid the tempera-ture rise	Traffic and temper-ature of nodes	Temperature rise, energy consump-tion, delivery delay, delivered packet rate	TSHR, TLQOS/NS-2		✓				Overload caused by periodic control messages
[27]	MTR 2017	Support mobility and avoid the tem-perature rise	The temperature of nodes and the probability of joining the sink	Delivery delay, delivered packet rate, number of hotspots vs. num-ber of dynamic nodes	LTR/C++				✓		Network overload, high end-to-end delay, creation of hotspots

(*continued on next page*)

Table 1. (continued)

Ref.	Protocol Year	Objective/ Methodology	Routing depends on	Performance metrics	Compared with/ Simulation tool	Packet rejection	Control messages	Data priority	Mobility support	Relay nodes	Limitation
[28]	TAR-SS 2018	Overcome the energy hole problem	Temperature of nodes	Delivered packets rate, average delivery delay, average residual energy, network temperature	TSHR, M-ATTEMPT/ OMNeT++		✓	✓			High load, the secondary sink run-out quickly, not suitable for high traffic networks
[30]	ATAR 2019	Balance the temperature rise between the network nodes	Temperature of nodes	Temperature rise and throughput	SHR, TARA, MRRP/CASTALIA		✓			✓	Additional costs caused by the formation of ring levels, the priority of messages neglected
[31]	TARALG 2019	Ensure packet priority while avoiding the rise of temperature of nodes	A function of (temperature, energy, number of hops)	Network lifetime, energy consumption, delivered packets, hotspot generation rate, temperature rise, number of hops	TARA, LTR, ALTR/ MATLAB	✓	✓				Risk of losing important data due to the packet rejection mechanism
[32]	TAEO-A 2019	Reduce the overheating effect and increase the network reliability	Energy and temperature of nodes, distance to the sink	Temperature rise, energy consumption, delivery delay, delivered packet rate	ATAR, SIMPLE/ NOT SPECIFIED						Data priority neglected
[33]	HTTRP 2020	Extend network lifetime, avoid temperature rise and achieve a high throughput	Energy and temperature of nodes	Network lifetime, charge balancing, throughput, number of generated hotspots	TARA/MATLAB			✓			Cannot ensure the best end-to-end delay
[34]	OPOT 2020	Achieve good performance regarding temperature rise, power consumption and delivery delay	Temperature of nodes, distance to sink, and energy of nodes	Temperature variations, power consumption, node lifetime, node lifetime, and high-priority data reception ratio	TARA, LTR/ MATLAB			✓			Missing explanation on how information of neighbors (energy and temperature) is maintained up-to-date
[35]	ATAR 2021	Provide energy efficiency and thermal awareness by adjusting the TP	RSSI level	Sink position, received packets vs. TP, and heating ratio	LSE-TPC, MPR/ CASTALIA						Data priority ignored, temperature and energy of nodes neglected in the route selection process
[36]	mobTHE 2021	Support mobility, avoid the temperature rise and preserve the energy of nodes	Energy and temperature of nodes and link quality	Temperature rise, network lifetime, throughput, and overall residual energy	THE, iM-Simple/ MATLAB		✓	✓	✓		Overload caused by synchronization messages

strategy adopted by the majority of TARPs is based on *waiting*. The solution implemented when a node has all its neighboring nodes as hotspots is to wait (i.e., the node must wait for the temperature to drop to establish the link with a neighbor again). This waiting leads to a high data delivery delay. Therefore, more research is highly required to find effective solutions to reduce delivery delays.

6.5. Universal thermal-aware solution

The vital factor considered by all TARPs is temperature. However, depending on the application requirements, there are other desired design aspects such as network lifetime, delivery delay, number of rejected/received packets, and number of heated nodes. Integrating all these design aspects into one implementation is an important research issue that is quite challenging.

7. Conclusion

Routing in WBANs has gained increased attention in the last decade and a half. Several protocols have been developed to meet the different requirements and specificities of WBANs. This paper reviews TARPs proposed to reduce node overheating, with an emphasis on the most recent ones. A detailed description, operating principles, and advantages and disadvantages of each protocol have been provided. The comparison made between these routing protocols has highlighted various literature gaps and vital key points. For example, it was noticed that most TARPs ignore the energy of nodes in the routing process except the most recent ones (TARALG, TAEO-A, HTTRP, and OPOT). This ignorance justifies the poor WBAN lifetime achieved by the earliest protocols. Furthermore, despite its crucial importance, node mobility has received little attention; only a few recent works (MTR and mobTHE) attempted to address this issue.

Finally, routing in WBAN remains an open research question. More research is needed to find the optimal routing solutions that can provide better performance regarding: network lifetime, delivery delay, packet loss, mobility support, fault-tolerance, and temperature rise in order to ensure the safe use of WBANs. This survey paper may contribute to a better understanding that can help in the development of new efficient TARPs.

Conflicts of interest

None.

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