A Review of Routing Protocols in Wireless Body Area Networks

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***Abstract*—Recent technological advancements in wireless communication, integrated circuits and Micro-Electro-Mechanical Systems (MEMs) has enabled miniaturized, low-power, intelligent, invasive/ non-invasive micro and nano-technology sensor nodes placed in or on the human body for use in monitoring body function and its immediate environment referred to as Body Area Networks (BANs). BANs face many stringent requirements in terms of delay, power, temperature and network lifetime which need to be taken into serious consideration in the design of different protocols. Since routing protocols play an important role in the overall system performance in terms of delay, power consumption, temperature and so on, a thorough study on existing routing protocols in BANs is necessary. Also, the specific challenges of BANs necessitates the design of new routing protocols specifically designed for BANs. This paper provides a survey of existing routing protocols mainly proposed for BANs. These protocols are further classified into five main categories namely, temperature based, cross-layer, cluster based, cost-effective and QoS-based routing, where each protocol is described under its specified category. Also, comparison among routing protocols in each category is given.**

***Index Terms*—IEEE 802.15.6, Body Area Networks, BANs, Wireless Sensor Networks, Mobile Ad Hoc Networks**

I. INTRODUCTION

Sensors in BANs can either be implanted in the human tissue (in-body) or strategically placed on the body (on-body). Either approach requires considering the effect of radiation emitted by wireless transceivers on the body tissue for human safety. In the in-body case, relaying or transmission of data to neighbor nodes may lead to average temperature rise which may have undesirable effects on human tissue given prolonged operation of the sensor nodes [1]. One solution is to disseminate data transmission in the entire network instead of relaying on some predefined routes. This avoids a dramatic increase in the temperature of sensors located in specific areas. However, such a solution increases overall system overhead and system complexity that should be minimized for BAN. Additionally, the severe path loss of radio signals in the surrounding of a human body necessitates the need of multihop communication in BANs as their direct transmission will come at high communication costs [1, 2].

Routing protocols in WSNs [3] and MANETs [4] have been excessively studied in the past few years. However, the stringent requirements of BANs imposes certain constraints on the design of their routing protocol which leads to novel challenges in routing which have not been met through routing protocol in WSNs and MANETs. WSNs consider minimal routing overhead and maximal throughput more significant than minimal energy consumption [5]. On the other hand, energy efficient routing protocols in MANETs consider finding routes to minimize energy consumption in cases with small energy resources. Unfortunately, they do not consider the required energy to receive and transmit a symbol over a wireless link and operations required for memory access, data processing and measurements [5]. WSNs assume homogeneous nodes comprise the network, whereas BAN nodes are heterogeneous and have varying capability with respect to data rate and available energy [6]. Mobility in WSNs may be on the order of meters to tens of meters, whereas in BANs movement is on the order of tens of centimeters [5, 6]. Additionally, BAN routing must consider variations in body movement, effects of radiation on tissue heating and limited energy resources to provide efficient usage of available resources to further reduce the intervals of battery charging, enhance network lifetime and develop a user-friendly system. Hence, even though the general characteristics of BANs are somehow similar to MANETs and WSNs, the unique differences amongst them with BANs requires novel solutions in their routing protocols.

In the past decade, several routing protocols have been proposed for BANs that can be classified with respect to their aims. The first category is *temperature based routing* protocols which are mainly designed to minimize the local or overall system temperature rise. In fact, the idea behind these protocols is to route data from different routes to avoid a dramatic temperature rise in some sensors leading to human tissue damage and depletion of the node. However, these protocols suffer from system complexity and overhead which dramatically increases with higher number of nodes. The second class is *cluster-*

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based routing protocols which try to divide nodes in BANs into different clusters and assign a cluster-head for each cluster and route data from sensor to the sink through the cluster-heads. These protocols aim to minimize the number of direct transmissions from sensors to the base station. However, the large amount of overhead and delay required for cluster selection are main drawbacks of these protocols.

Cross layer routing which is the third category of BAN routing protocols discussed in this paper, combines the challenges in routing with medium access issues. Although these protocols achiever high throughput, low energy consumption and a relatively fixed end-to-end delay, they cannot provide high performance in cases of body motion and high path loss in some scenarios. *Cost-effective routing* protocols periodically update a cost function based on cost-effective information and find their route amongst routes with minimum cost. These protocols suffer from large number of transmissions required for updating cost-effective information. The last category is *QoS-based routing* protocol which mainly provides separate modules for different QoS metrics that operate in coordination with each other. Hence, they provide higher reliability, lower end-to-end delay and higher packet delivery ratio. These protocols mainly suffer from high complexity due to the design of several modules based on different QoS metrics.

We provide a detailed review of each protocol in its specified category, compare protocols within each category and describe their main advantages and drawbacks. As temperature routing protocols try to minimize the overall or local temperature rise in BANs and do not consider link quality or other system parameters, they may not satisfy all the requirements in BAN routing. Cross-layer and cluster based protocols require a large amount of overhead to exchange network information between nodes and do not consider temperature effects of the protocol on the skin and so do not fulfill all requirements of routing in BANs. Cost-effective protocols can not provide high throughput without minimum overhead and energy consumption. QoS routing protocols require too much information that leads to high energy consumption and huge overhead. In fact, each classification of routing protocols only tries to satisfy a specific requirement in BANs. This encourages us to find new routing protocols that meet all requirements of BANs. This paper takes the first step in this regard by providing a detailed review on existing routing protocols in BANs which is essential to gain the overall knowledge of challenges in BAN routing and possible solutions in each case.

The rest of this paper is organized as follows. Section II provides background information on BANs. Section III describes challenges of routing in BANs. BAN specific temperature routing protocols are described in Section IV. Section V describes cluster based routing protocols in BANs. Cross-layer routing protocols are described in Section VI. Section VII and Section VIII describes cost-effective and QoS-based routing protocols in BANs, respectively. In Section IX, we provide a comparison of routing in BANs with WSN and MANET routing. Section X concludes the paper.

II. Background

BANs have a huge potential to revolutionize the future of health care monitoring by diagnosing many life threatening diseases and providing real-time patient monitoring [7]. Demographers have predicted that people age 65 and over in 2025 will double the 357 million population in 1901 and become 761 million. This implies the fact that by mid-century, medical care will become a major issue. By 2009, the health care expenditure in the United States was about 2.9 trillion and is estimated to become 4 trillion by 2015, almost 20% of the gross domestic product. Moreover, based on the advances in technology in microelectronic miniaturization, integration, sensors, the Internet and wireless networking; the deployment and service of health care services will be fundamentally changed and modernized. Via the use of BANs, health care systems can be augmented to manage illness and react to crisis rather than just wellness [8, 9].

A *node* in a body area network is referred to an independent device with communication capability. Nodes in BANs can be classified into three different categories based on their functionality, implementation and role in the network. In terms of functionality, there are the three types of nodes: a) *Sensors* that measure certain parameters in one's body internally or externally and gather and respond to data on a physical stimuli, process necessary data and provide wireless response to information. b) *Actuator* which interacts with the user once it receives data from the sensors [6]. c) *Personal Device (PD)* which collects all information received from sensors and actuators and handles interaction with other users.

In terms of implementation nodes are classified into three classes of *Implant Node*, *Body Surface Node* and *External Node*; which are implanted in the human body and, 2cm away from the body and farther away from the it, respectively [10, 11]. Nodes in BANs can also be classified into three types based on their role in the network: a) *Coordinator* which is a gateway to the outside world or another BAN, b) *End Nodes* which are only capable of performing their embedded application, c) *Routers* are intermediate nodes which have a parent node and a few child nodes through which they relay messages.

Based on the IEEE 802.15.6 working group nodes in BANs are considered to operate in either a one-hop or two-hop star topology with the node in the center of the star being placed on a location like the waist [12, 13]. As for communication architecture, BANs can be separated into three different tiers as follows: *Intra-BAN* (tier-1), *Inter-BAN* (tier-2) and *Extra-BAN* (tier-3) shown in Fig. 1. These communication tiers cover multiple design issues in facilitating an efficient, component-based system for BANs [14]. As shown in Fig.1, the devices of BANs are scattered all over the body in a centralized network

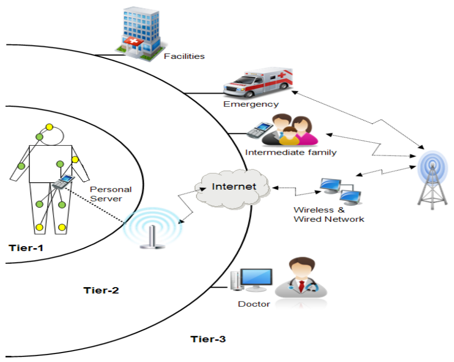

Fig. 1. Communication Tiers in a Body Area Network

architecture where the precise location of a device is application specific [14].

III. Routing Challenges in BANs

BANs span a wide area of medical and non-medical applications from sport and entertainment to ubiquitous health care, military and many more. The main goal of all BAN applications is to improve one's quality of life. However, BANs applications have different architectures, technological requirements, constraints and goals. This Section covers a general view of challenges in different BAN applications.

1) Postural Body Movements: The link quality between nodes in BANs varies as a function of time due to postural body movements [15]. Thus, the proposed routing algorithm should be adaptive to different topology changes. In this regard, the authors of [16] have considered BANs to be in the category of Delay Tolerant Networks (DTN) due to disconnection and frequent partitioning concluded from postural body movements. Moreover, body segments and clothing have been shown to negatively intensify RF attenuation to signal blockage.

2) Efficient Transmission Range: Low RF transmission range leads to disconnection and frequent partitioning among sensors in BANs which leads to similar performance to DTNs [16]. More specifically, if the transmission range of sensor nodes in a BAN is less than a threshold value, the choice of the next sensors for routing is reduced which causes higher number of transmissions to obtain a route leading to an overall average temperature rise. Moreover, the lower the number of neighbors the less the probability for packets to arrive at the destination within a certain hop count. Hence, packets would take longer to arrive at the destination and the average temperature of the network will increase [1].

3) Limitation of Resources: The bandwidth in BANs is limited and varies with interference, noise and fading. Hence, the proposed routing protocol needs to be aware of the limitation on network control, energy and data gathered as the nodes in BANs may deplete due to unavailable memory, battery and bandwidth which may affect Quality of Service (QoS) [5].

4) Interference and Temperature Rise: In terms of computing power and available energy, the energy level of nodes needs to be taken into account in the proposed routing protocol. The transmission power of nodes needs to be extremely low in order to avoid tissue heating and minimize interference [5].

5) Limitation of Packet Hop Count: Based on the IEEE standard draft of IEEE 802.15.6 [17], only one-hop or two-hop communication is defined for BANs. Multi-hopping will increase overall system reliability by providing stronger links. However, the larger number of hops the higher the energy consumption [2]. Most proposed BAN routing protocols have not considered the limitation of number of hops.

6) Local Energy Awareness: The proposed routing algorithm should not rely on one route and one node in the network but has to further disperse its communication data to avoid total power usage of a specific nodes leading to node failure.

7) Global Network Lifetime: Network lifetime in BANs is defined as the time interval between which the network starts working to the time the first node dies [15]. Network lifetime is of greater importance in BANs compared to WSNs and Personal Area Networks (PAN) as devices are expected to operate over a longer period e.g. charging and battery replacement is not feasible in implantable medical devices [12]. In this regard, simulation results in various papers have clarified the improvement of network lifetime through multihop relay networks [18].

8) Heterogenous Environment: Nodes in BANs can be heterogenous. More specifically the memory and power consumption of nodes may be different from one another, which imposes several challenges to QoS in BANs [6].

IV. Temperature Based Routing

Radio signals generated through wireless communication generate magnetic and electric fields. The exposure of electromagnetic fields results in radiation absorption of the human tissue leading to temperature rise [19]. This will reduce blood flow and cause thermal damage to more sensitive organs. Prolonged temperature rise inside the human body tissue can lead to damage, growth of certain types of bacteria, effect enzymatic reactions and reduce blood flow in some organs [20]. The amount of radiation energy absorbed by human tissue given in (1) is referred as the Specific Absorption Rate (SAR) [19].

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

where σ is the electrical conductivity of tissue, E is the electric field induced by radiation and ρ is the density of tissue. Experiments have shown exposure to SAR of 8 W/kg for 15 minutes can cause significant tissue damage [19]. Hence, BAN routing protocols must actively decrease temperature and radiation emission. More specifically, even routes with short delay and light traffic might not be efficient in terms of temperature which makes routing and forwarding intolerable for the nodes. The common objective of all temperature routing protocols reviewed in this section is to maintain low temperature among sensor nodes by avoiding routing on hot spots.

A. Thermal-aware routing algorithm (TARA)

The TARA [19] protocol has been considered for in-body sensor networks and considers sensor locations and cluster leadership history to minimize the hazardous effects of temperature rise on the human tissue. It measures temperature changes of its neighboring sensor nodes through monitoring neighbors packet count, calculation of communication radiation and power consumption. TARA aims to reduce the possibility of overheating and handles packet transmission in temperature rise by defining hotspots as areas that exceed a certain temperature due to data communication. Accordingly, it aims to specify paths to detour around the hotpots. As can be seen in Fig.2, in cases where packets arrived at nodes surrounded by hot spots, they are sent back to the sender and an alternate path is specified to detour the routes. After the hot spots have been cooled down to a certain limit, they can be considered in later routing. TARA uses the Finite-Difference Time-Domain (FDTD) [21, 22] method to measure the Specific Absorption Rate (SAR) and temperature rise of each node. This protocol measures temperature rise by using the FDTD and Pennes bioheat Equation shown in (2) [23], by which it discretizes the problem space into small grids with a pair of coordinates (i, j).

In (2), σ is the discretized space step (size of grid), σ_t is the discretized time step, b is the blood perfusion constant, ρ is the mass density, C_p is the specific tissue heat, K is the thermal conductivity of the tissue, T_b is the temperature of the tissue and the blood; and P_c is the heat generated from power dissipation of circuitry. Based on (2), the temperature of grid point (i, j) at time $m+1$ is a function of the temperature of its surrounding grid points $(i+1, j), (i, j+1), (i-1, j)$ and $(i, j-1)$ at time m. TARA has shown to have low maximum temperature rise and small average temperature rise which makes it a safe routing protocol for use in in-body BANs. Also, the thermal-aware capability of TARA leads to better load balancing and less traffic congestion [19].

However, since TARA withholds packets from hot spot regions and finds routes through alternate paths, there is an average increase in the number of transmissions and overall network temperature. Additionally, TARA only considers temperature as a metric, has low network lifetime, high end-to-end delay, low reliability, high packet loss ratio and does not consider power efficiency and link probability.

B. Least Temperature Routing (LTR)

Bag et. al [24], have proposed the LTR protocol which is a thermal aware routing protocol for BANs. LTR defines hot spots as areas which have high temperature due to data communication focus. Each node in LTR is assumed to have knowledge of the temperature of its neighbor nodes, similar to TARA. As shown in Fig. 3, unlike TARA, LTR chooses its routes from neighbor nodes with the lowest temperature. Hence, it sets its path to the coolest neighbor without involving routing loops. In fact, a hop-count is specified for each packet and is incremented by the value of one each time a node forwards a packet. In order to maintain the network bandwidth constraint, the packet is discarded if it has exceeded the threshold value of MAX_HOPS, which is relative to the diameter of the network. LTR also provides its packets with tables that keep track of the sensor nodes through which the packets have passed and avoids getting into infinite loops.

However, as nodes in LTR forward packets to nodes with lowest temperature until the destination is reached, there is potential for significant power consumption, overall temperature rise and waste of bandwidth throughout the network as most nodes will be involved in routing. Also, LTR does not ensure that packets are forwarded in the direction of the destination, consequently the route towards the destination is less optimal. Additionally, the temperature of sensor nodes is variable over time which will increase the end to end delay. LTR is considered a greedy approach to routing that is not globally optimal, but may be locally optimal [1].

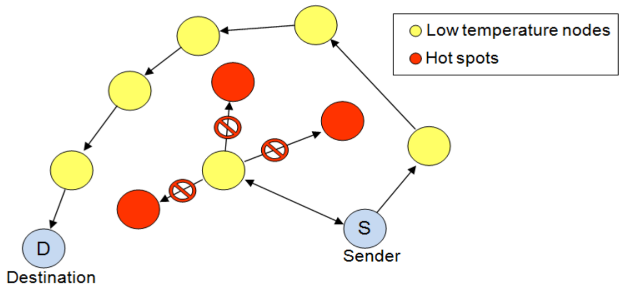

Fig. 2. TARA

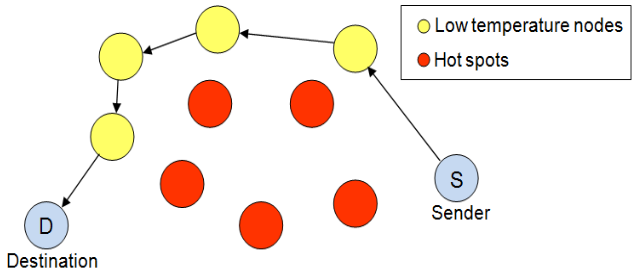

Fig. 3. LTR

C. Adaptive least temperature routing (ALTR)

Another temperature based routing scheme was recently proposed in [24], namely ALTR. It is similar to LTR in specifying MAX_HOPs_COUNT for packets being routed to not exceed the MAX_HOPs_ADAPTIVE. If the number of hops is less than or equal to MAX_HOPs_ADAPTIVE, the same rules as the LTR

$$T^{m+1}(i,j) = [1 - \frac{\sigma_t b}{\rho C_p} - \frac{4\sigma_t K}{\rho C_p \sigma^2}]T^m(i,j) + \frac{\sigma_t}{C_p} SAR + \frac{\sigma_t b}{\rho C_p} T_b + \frac{\sigma}{\rho C_p} P_c + \frac{\sigma_t K}{\rho C_p \sigma^2}[T^m(i+1,j) + T^m(i,j+1) + T^m(i-1,j) + T^m(i,j-1)] \quad (2)$$

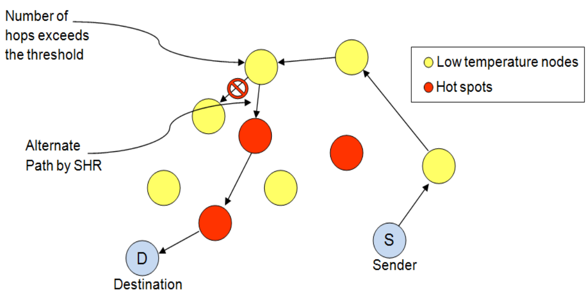

Fig. 4. ALTR

algorithm apply. Whereas, in cases where the hop count is higher than MAX_HOPs_ADAPTIVE, the Shortest Hop algorithm (SHR) is used [24]. An example of routing in ALTR is shown in Fig. 4. ALTR also differs from LTR in being adaptive to different topologies, as it uses a proactive delay strategy to cool down the temperature of nodes in a ring topology which tends to increase rapidly by passing the same path repeatedly. In cases where a node receives a packet when even its coolest neighbor has a high temperature, the node delays the packet by one unit of time before sending it to its coolest neighbor. Thus, a minor increase in packet delivery delay is traded off for the average temperature of the network. Even with a hop count specification in ALTR, network bandwidth is wasted when routes calculated from SHR go through hot spots. Also, as ALTR sends packets to neighbors with minimum temperature, the overall network temperature and number of hops will eventually increase. In fact, this algorithm does not guarantee that packets are routed towards the destination which leads to increase in sensor temperature and hop count.

ALTR, LTR and TARA do not optimize routing in terms of reliability, delay or efficiency. More specifically, the excessive hop count leads to more than 50% packet loss ratio which results in average network temperature rise, energy wastage and low packet delivery ratio.

LTR and ALTR have shown to have lower temperature rise at all packet arrival rates compared to TARA and SHR. SHR has higher temperature rise as it ignores temperature rise and aims to find the shortest route whereas LTR and ALTR have better performance even at high packet arrival rates as they route packets through cooler nodes from the start [24].

LTR and ALTR have better end-to-end delay than TARA at higher packet arrival rate. However, ALTR has considerably lower delay than LTR due to its adaptive nature. Also, TARA has the highest power consumption compared to LTR and ALTR as it withdraws packets from heated regions and detours them which leads to higher power consumption [24]. Additionally, TARA experiences larger number of hops and higher packet loss compared to LTR and ALTR as it reroutes data from heated regions.

D. Least Total Route Temperature (LTRT)

LTRT is a temperature aware routing protocol proposed in [1] which basically is a smart hybrid of LTR and SHR. LTRT aims to optimize issues related total temperature rise and redundant hops. Hence, it is designed to reduce hop count to maintain network bandwidth and select routes with minimum temperature from sender to destination. LTRT uses the single source shortest path (SSSP) algorithms of graph theory, Dijkstra's algorithm, to calculate its routes and uses the routes for further transmission. Basically, LTRT translates the temperature of sensors into graph weights which eventually lead to minimum temperature routes. The temperature of each sensor node is assigned as the weight of that sensor node. It then transfers the weight of its sensor through predefined outgoing edges that connect the nodes (Fig. 5). The step by step procedure of route allocation in LTRT is as follows:

a. Observe communication activity of neighbor sensor nodes to assign the temperature of sensor nodes as the weight of each sensor node.
b. Transfer weight of the sensor nodes to the weight of outgoing edges connected to the node.
c. Find least temperature routes from sender to destination nodes by applying single shortest path algorithm to the configured graph.
d. Update routes periodically to avoid excessive temperature rise of sensor nodes and maintain topology changes related to node mobility.

Simulation results in [1] have shown LTRT to have lower average temperature rise, hop count per packet compared to ALTR and LTR. This is because of specifying a route to the destination in LTRT before packet transmission which affects the maximum number of hops required to reach the destination node and the average temperature rise in the network. Since LTRT and ALTR are designed to not drop any packets in the routing procedure, their packet loss ratio is nearly zero. Whereas, LTR has a higher packet loss as it discards some packets and the packets take more time to reach the destination node which inevitably exceeds the maximum hop count threshold. Even with increasing the number of nodes, LTRT has lower average temperature rise compared to ALTR and LTR.

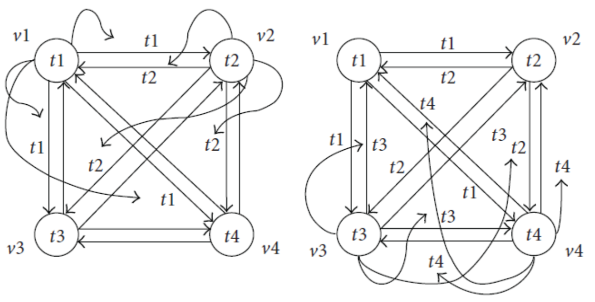
Fig. 5. LTRT [1]

LTR provides better energy efficiency and lower temperature rise compared to the aforementioned algorithms. However, overhead is a major drawback as each node has to have knowledge of the temperature of all other nodes. Unfortunately, energy consumption is not investigated in the LTRT.

E. Hotspot Preventing Routing (HPR)

HPR [20] is a biomedical sensor network routing protocol for delay sensitive applications like medical monitoring. It aims to avoid hotspot formation and decrease average packet delay. HPR routes packets through the shortest hop from the sender node to the destination via minimum hops unless a hotspot exists in that path. However, the packet is discarded if the hopcount exceeds *MAX_HOPs*. Packets also maintain a list of most recently visited nodes to avoid loops. Temperature change of neighbor nodes is computed through overhearing the number of transmissions of neighbors and estimation of number of packets transmitted in a certain time interval.

The procedure of route calculation in HPR is completed through a *setup phase* and a *routing phase*. In the *setup phase*, information exchange relative to the initial temperature of the nodes and shortest path is provided and routing tables are built. The *routing phase* considers the following:

- *If* a neighbor node is the destination of a packet, the packet is directly forwarded to the destination
- *Else If (temperature of next hop in shortest path to destination* $\leq$ *current node temperature + threshold):* packet is routed through next hop in the shortest path to destination.
- *Else If (temperature of next hop in shortest path to destination* $\geq$ *current node temperature + threshold):* The node realizes that this path faces a hotspot in its route and routes the packet such that it bypasses the hotspot. Hence, the packet is forwarded to a neighbor node with the least temperature (coolest neighbor).

The *threshold* value is dynamically calculated in (3) from the temperature of neighbor nodes (C_1) and the local load (number of packets routed by a node over a past time window). Hence, the threshold value depends on the equal weight of these two components. So, the load is handled through a node's temperature which is based on the number of packets routed over a past window (C_2).

$$\text{threshold value} = 0.5 \times C_1 + 0.5 \times C_2 \qquad (3)$$

where $C_1 = K_1\sqrt{avg_n}$, $C_2 = K_2\sqrt{temp_n}$, avg_n is the average temperature of the node's neighbors, $temp_n$ is the temperature of a node, K_1 and K_2 are constants set through experiments.

Simulations in [20] have compared HPR to TARA and SHR. TARA has shown to have better performance than HPR and SHR at high packet arrival rates but has significantly high packet loss and packet delivery delay. Whereas HPR has almost zero packet loss, very low packet delivery delay and decreases the maximum temperature rise of the nodes. TARA withdraws packets from hot spot regions and detours them through alternate paths which results in more communication in the network that creates more hotspots, higher packet loss and higher packet delivery delay. HPR chooses its routes via bypassing the high temperature regions and choosing the shortest path from the sender node to the destination node. Routes are dynamically established based on network traffic conditions. Hence, HPR has low packet delivery delay, prevents the formation of hotspots and avoids temperature rise.

HPR is further extended for use in Networks-on-Chip (NoC) in [25] as a hotspot preventing adaptive routing algorithm for Networks-on-Chip, namely HPAR. The procedure of route calculation in HPAR is similar to HPR and is completed through a setup phase and a routing phase. However, information exchange is done among routers related to the associate routers and unique *module_ids* assigned to modules or components. HPAR calculates its threshold value from (3).

F. Routing algorithm for networks of homogenous and Id-less biomedical sensor nodes (RAIN)

The authors of [26] have proposed the RAIN routing algorithm for networks of homogeneous and Id-less biomedical sensor nodes. RAIN is fault tolerant and operates efficiently even though some of its nodes die as their energy depletes. RAIN operates in three phases: setup phase, routing phase and status update phase. In the *setup phase*, each node uses a random number generator to originate a random number which is assigned as *node-id* in the operational lifetime of the node. All nodes distribute their *ids* throughout the network through their *Hello* messages.The $id = 0$ is given to the sink node. The idea of the *routing phase* is to assign a unique *packet-id* to each packet generated by a node with the format $[N, T, R]$, where N is the node-id of the node that this packet originated from, T is the time the packet has been generated and R is a random number. A *hop-count* is also specified which is incremented by 1 at each hop. Once a packet reaches a node its *hop-count* is checked and route calculation is done as follows:

TABLE I
COMPARISON OF TEMPERATURE ROUTING PROTOCOLS IN BANS

Characteristics	Temperature Routing						
	TARA	LTR	ALTR	LTRT	HPR	RAIN	TSHR
Network Lifetime	Very Low	Low	Low	Very High	Low	High	Very High
End-to-End Delay	Very High	High	High (lower than LTR)	Low	Low	Low	High
Loop Prevention	No	Yes	Yes	Yes	Yes	Yes	Yes
Limitation of Number of Hops	No	Yes	Yes	Yes	Yes	Yes	Yes
Power Consumption	Very High	High	High	Low	High	Low	Low
Knowledge of Temperature of Neighbor Nodes	Yes	Yes	Yes	Estimates	Yes	Estimates	Estimates
Hot Spot Avoidance	No	Yes	Yes	No	Yes	Yes	Yes
Average Temperature Rise	Very High	High	Low	Very Low	Very Low	Very Low	Very Low
PDR	Low	Low	Very High	Very High	Very High	Very High	Very High
Hop Count	Very High	Very High	High	Low	Very Low	High	Low

- *If* (*hop-count*$>$ TTL (Time to Live)): packet is discarded. The *TTL* value depends on the network diameter.
- *If* (*hop-count*$>$ HOP_THRESH & *packet-id* is not in *queue-id*): *packet-id* is added to *queue-id*
- *If* (*SINK* node is in the list of neighbors of the node & the packet has not been dropped): packet is delivered to the *SINK*
- *Else If* (*SINK* node is not in the list of neighbors of the node): packet is delivered to the n^{th} neighbor instead of the sender node with the probability p_n.

$$p_n = \frac{1}{\left(\frac{t_n}{T_L} \times K\right) + 1}, \tag{4}$$

  where t_n is the neighbor's estimated temperature, T_L is the average estimated temperature of local nodes and K is a constant value set by experiments.
- *If* (packet is not routed to any neighbor node): packet is delivered to the neighbor estimated to have the least temperature or coolest neighbor.

A status update phase is specified to maintain the energy of nodes around the sink to eliminate the energy-hole issue and avoid reception of duplicate packets at the sink. Once a *SINK* node receives a packet, an *update* message is broadcasted to neighbors that consist of the *packet-id* of the received packet. Upon receiving an *update* message, each node adds the *packet-id* in the message to the *queue-id*.

The *SINK* and neighbor nodes in RAIN consume much less power than all other nodes in the network which is convenient in avoiding energy holes. Also, nodes in RAIN maintain an estimation of the temperature of neighbor nodes and the probability of routing packets to heated nodes is kept very low. Hence, these nodes will have time to cool down as well as avoiding redundant packet transmissions resulting in low energy consumption. Also, since packets are detoured from heated nodes, there is higher probability for them to be delivered which increases the packet delivery ratio and has shown to have acceptable delay.

G. Thermal-Aware Shortest Hop Routing (TSHR)

TSHR [27] has been proposed for applications that require a high priority for delivering a packet to the destination and restransmiting the packet when it is dropped. Two phases of the TSHR algorithm are as follows:

1) *Setup Phase* where each node build its routing table.
2) *Routing Phase* where nodes try to use the shortest path to the destination.

Also, two thresholds are defined for the temperature of the nodes: 1) T_{Dn} which is a dynamic threshold based on node's temperature and the temperature of its neighbor nodes and can be calculated by the summation of a threshold and the node's temperature calculated in (5).

$$T_{Dn} = temp_n + 0.25\sqrt{(temp_n)} + 0.25\sqrt{(avg_n)} \tag{5}$$

2) T_s is a fixed value that specifies that the nodes must not exceed a certain threshold. In cases where a node's temperature exceeds T_{Dn}, the neighbor is considered to be a hotspot. The procedure of route allocation in TSHR is as follows:

- If (*destination of a packet* = one of the neighbors)
  next_hop = destination
  go to step SEND
  next_hop=neighbor in the shortest hop path
  calculate TD_n
- If(hop$>$ remain_hop - k)
  go to step SEND
- If(next_hop $\times$ temperature $< TD_n$)
  go to step SEND
  next_hop=coolest node which is not visited

SEND:

- If(next_hop temperature $<$ TS)
  send to next_hop
- Else (go to step SEND)

Simulation results have shown TSHR has the highest lifetime and its packet drop is nearly zero. However, packet delivery delay and packet arrival rate is higher than HPR, but TSHR has lower maximum temperature rise.

A comparison on temperature routing algorithms in BANs is given in Table I where LTRT has shown to have comparatively better performance amongst all the proposed protocols.

V. Cluster-based Routing

A. Anybody

Anybody [28] is a cluster-based routing protocol that uses clusters to gather data instead of making direct communication with their base station. The clusters are chosen randomly in time which spreads energy dissipation through the entire network as cluster heads collect all data and then send it to the base station. Anybody further considers a virtual backbone network of cluster heads by which it changes the cluster head selection. The step by step procedure of route allocation in Anybody is as follows:

(1). *Neighbor Discovery:*

In stage 1, each node broadcasts $hello_1$ messages consisting of its unique identifier, waits for $hello_1$ messages in a given time frame, and relays $hello_1$ messages of its one-hop neighbors via sending $hello_2$ messages in the second time frame. At this stage, each node has gained knowledge of its two-hop neighbors and builds its *connectivity graph*.

(2). *Density Calculation:*

In stage 2, each node calculates its density from (6) and sends it via $hello_3$ messages throughout the network and receives the density of other nodes in the network.

$$\text{density} = \frac{\text{number of links}}{\text{number of 2-hop neighbors}} \quad (6)$$

(3). *Contacting Clusterhead:*

In stage 3, each node sends a *join* message along with the list of its one hop neighbors to its neighbor with highest density. The *join* messages are continuously relayed until they reach the node with highest density. These paths form an *intra-cluster gradient* and will be used for intra-cluster communication. Hence, clusters and cluster heads are formed among local nodes. The cluster heads have knowledge of the nodes attached to them as well the neighbor list of each one.

(4). *Setting up the backbone:*

In stage 4, some nodes will be chosen as Gateway (GW) nodes to connect the independent clusters with each other. Each clusterhead checks its cluster members and selects those that have a neighbor outside the cluster. Hence, a *GW inform message* will be sent to the elected nodes. GW nodes are responsible for communication among the clusters and build a virtual backbone through their virtual communication. Each GW node sends messages it receives from its clusterhead to the gateway node it is connected with and messages its receives from another cluster to its clusterhead through its *intra-cluster gradient*.

(5). *Setting up the routing paths:*

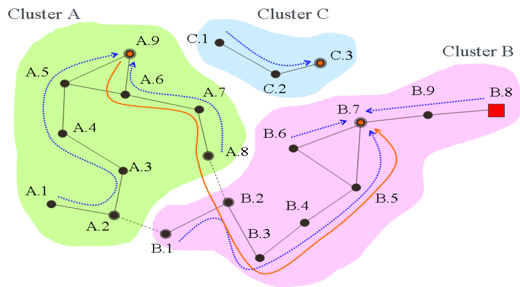

Fig. 6. ANYBODY [28]

In stage 5 (the last stage), routing paths are formed via $gradient\_setup$ messages: $gradient\_setup_1$ from sink node to its clusterhead, $gradient\_setup_2$ from cluster head to its connected backbone links, $gradient\_setup_3$ from other clusters till all clusterheads have sent a $gradient\_setup$ message which sets up *inter-cluster-gradients* (Fig. 6). Therefore the route for a message flow in Anybody is in the following order: *sender node, sender's clusterhead, other clusterheads, sink's clusterhead and finally the sink.*

The features of Anybody can be extended for use in heterogenous networks by assigning different tasks to different nodes, enhancing energy efficiency by switching off redundant nodes and using data aggregation methods to eliminate and buffer the messages.

Anybody has the major advantage of keeping the number of clusters low with increase in number of nodes. However, reliability and energy efficiency has not been thoroughly investigated. Also, this protocol is not optimized for BANs and has high delay and significant overhead which is inconvenient for BANs due their stringent constraints in bandwidth, computational power and energy.

B. Hybrid Indirect Transmission (HIT)

Culpepper et al [29, 30] have proposed a cluster-based data gathering protocol that reduces the number of direct transmissions to the base station and uses parallel multihop indirect transmissions both within a cluster and among multiple adjacent clusters. The analysis of HIT and HIT_m (HIT with multiple clusters) have shown small network delay, high energy efficiency and high network lifetime.

The procedure of route calculation in HIT is described as follows: In the initial stage, one or multiple cluster-heads are chosen. The cluster-heads then send out their status throughout the network. Next, the upstream and downstream relation of the clusters are formed. Accordingly, multiple routes are setup within a cluster to the cluster-head. Then each node calculates its *blocking set*. The *blocking set* of node i is the list of nodes that are not allowed to transmit simultaneously with node i. More specifically, node i blocks node j only if

$$d(i, u_i) > d(i, u_j) \quad (7)$$

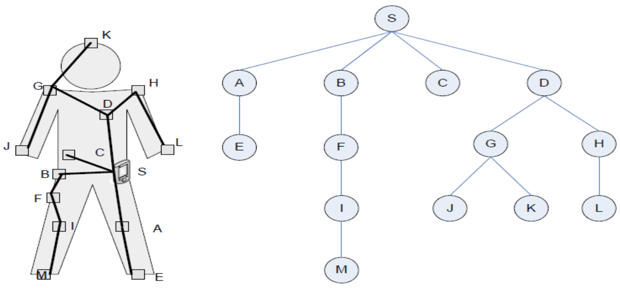

Fig. 7. WASP [2]

where u_j is the upstream neighbors of node j. Then, a TDMA schedule is computed for each node which allows maximum communication amongst nodes with parallel transmissions. Finally, nodes transmit to their upstream neighbors through the TDMA schedule previously assigned. Unfortunately, HIT requires more communication energy in dense networks, does not consider reliability and has conflicting interaction issues among the desired routes for specific applications and its communication routes [5].

VI. Cross Layer Routing

A. Wireless Autonomous Spanning Tree Protocol (WASP)

The WASP [2] protocol sets up a spanning tree and divides the time axis in slots, referred as *WASP-cycles*, in a distributed manner to provide traffic routing and medium access coordination using the same spanning tree which results in lower energy consumption and higher throughput (Fig. 7). Each node assigns a unique *WASP-scheme* message and sends to its child nodes informing them when they are allowed to use the link. Hence, these messages allow traffic control and increase resource request from parents of children which minimizes the coordination overhead. The children respond to the scheme by sending their own *WASP-scheme* based on the the sink *WASP-scheme* and the child node's requirements. It is important that the nodes are synchronized to avoid shifting. The *WASP-scheme* messages are different for sink and child nodes, but they usually consist of the following: (1) address of sender node (2) slots assigned to the children of the parent node where they send their *WASP-scheme* (3) silent period duration (4) forwarding received data to the sink (5) Contention slot (6) Acknowledgment sequence. WASP achieves up to 94% throughput, high packet delivery ratio, low energy consumption and fixed end to end delay. However, WASP does not consider link quality, mobility, load and does not support two way communication. Also overhead is a drawback which can be reduced with data aggregation techniques.

B. Controlling Access with Distributed slot Assignment protocol (CICADA)

CICADA [18, 31] is a low energy cross layer routing protocol specifically designed for BANs based on multi-hop TDMA scheduling and improves reliability through the definition of a lognormal distribution for link probability instead of a circular coverage region. It is an improvement to the WASP protocol as it considers two way communication. In CICADA, each node calculates two parameters for sending data and sends it to its parent node. One is the number of slots required to send data, α_n and the other is number of slots the node has to wait until it has received all data from its children, β_n. Based on these parameters, all nodes know when to send data. Additionally, each transmission cycle is divided into data and control subcycles which enhance mobility support as it provides the detection of parent or child loss, lower delays for joining a node and allows a maximum of 3 cycles to join the parent node.

In the data subcycles, each node sends its data based on the allocated time. In the control subcycle, the parent nodes broadcast a scheme to their child nodes to inform them of when to transmit data. Unlike WASP, the bottom nodes of the spanning tree are the first nodes to send their data. Hence, CICADA has been designed such that all packets reach the source in one cycle which leads to lower delay and routes data packets up its spanning tree to control medium access without the requirement of control packets. Also CICADA has much simpler computations for calculating the data period and waiting period compared to WASP which is significant for use in networks with scarce resources.

CICADA has modeled reliability by using scheme randomization and increasing the number of retransmissions [18]. Additionally, CICADA can be enhanced to support high traffic BANs which require low delay by sending data more often instead of local buffering [31]. In terms of energy efficiency, CICADA avoids collision, idle listening and overhearing via assigning slots in the control subcycle and using them in the data subcycle. Hence, all nodes will know of their sleep time, when to receive data, when to send data and when to switch on their radio.

However, CICADA has shown to have a high sleep ratio in cases with 50% or lower duty cycle. Also, longer duty cycles have higher packet loss in high packet generation rates and a major increase in number of retransmissions. Therefore, a tradeoff exists between energy efficiency and the desired throughput [18]. Also, all communication information in CICADA is sent in plain text instead of being protected and unauthorized nodes are capable of joining the network without authorization. An updated version of CICADA, namely CICADA-S has been designed in [32] to encounter the privacy and security issues that had not been considered in CICADA. CICADA-S has four main states in terms of security: secure initialization phase, sensor (re) joining the BAN, key update procedure within the BAN and a sensor leaving the BAN. These phases have little impact on the throughput and power consumption [32].

C. Timezone Coordinated Sleeping Mechanism (TICOSS)

TICOSS [33] sets all nodes as Full Functional Devices (FDD) and provides improvements to the IEEE 802.15.4

standard by offering configurable shortest path routing to the BAN coordinator, preserving energy and reducing hidden terminal collisions through V-scheduling (due to V-shape communication flow). This results in double the operation lifetime of IEEE 802.15.4 for high traffic scenarios and the extending IEEE 802.15.4 to support mobility. The idea of TICOSS is to provide timezone divisions based on the minimum hops required for packets to reach the coordinator when all nodes have joined the network. Both synchronization and timezone division can take place in the initialization phase as follows: an initial zone message is sent by the coordinator to neighboring nodes that consists of timing information and zone of the transmitter (TxZone). The nodes receiving this message set their timezone to TxZone+1, renew their internal clock and send a new zone message which consists of new timing information and TxZone+1 as the transmitter zone. Further receiving nodes continue this process.

TICOSS considers mobility, replacement and node deployment through setting a preset expiration time for a node's timezone when no zone update message is received by the node. The updates are stored in a table along with the sender's node ID, to discard and identify stale zone messages, and a timestamp to associate corrupt entries. The V-scheduling table assigns periods of node inactivity and activity to nodes timeslots which allows transmission and reception to occur in the same interval. Nodes in the same time slot are capable of using the same time slot for transmission.

D. Cross Layer MAC and Routing Protocol Co-Design for Biomedical Sensor Networks (BIOCOMM)

BIOCOMM [34] is a cross layer routing protocol designed based on the interaction of the MAC and network layer in biomedical sensor networks to optimize overall network performance. This interaction is achieved through a *Cross-layer Messaging Interface (CMI)* via which the MAC layer sends its status information to the network layer and vice-versa. More specifically, the network layer keeps track of the vacant space in it Buffer Space (BS) and this information is sent to the MAC layer through the CMI by which MAC layer becomes capable of assigning higher frame transmission priority to congested nodes to eliminate packet loss ratio in the network layer due to buffer overflow. Both the MAC and network layer each maintain *Neighbor Status Table* which is set to *Blocked* (B) or *Free* (F) via the MAC logic. Each modification in the Block and Free message is generated and sent via CMI to the network layer through which the network layer updates its status in its *Neighbor State Table*.

Each node tries to route packets to the destination via the least number of hops unless a sleeping node or a hotspot exists in the path. The procedure of route allocation in BIOCOMM is as follows:

- If (*hop_count* $>$ Time To Live (TTL)): The packet is dropped.
- Else If (Status of next-hop node in shortest path to sink is *Free* in *Neighbor Status Table*): 1) increment *hop_count*, 2) Send packet to next-hop node.
- Else If (Status of next-hop node in shortest path to sink is *Blocked* in *Neighbor Status Table*): 1) Increment *hop_count*, 2) Send packet to Last Active node (LA).

BIOCOMM-D provides certain modifications to BIOCOMM to reduce the average packet delay in delay sensitive applications. Both Biocomm and Biocomm-D have very low temperature rise for nodes in its network. However, Biocomm-D has comparatively higher temperature rise than Biocomm due to its attempt to reduce average packet delay.

Both Biocomm and Biocomm-D have significantly lower energy consumption (one-forth the energy consumption of HPR) which is due turning the radio of nodes off when they are asleep. In terms of delay, Biocomm has slightly higher delay than HPR which is resolved in Bicomm-D which has lower delay than both Biocomm and HPR as it drops packets that have been circulating in the network for a long time.

VII. Cost-effective routing

A. Opportunistic routing

In [15], the moving nature of the body is considered in the routing protocol through an opportunistic scheme that ensures high communication probability with the sink at all times. This protocol uses a simple system model where the sink node is placed on the wrist and moves forward and backward while running and walking. A relay node exists on the waist and a sensor node on the chest. Consequently, for the sensor node to be able to communicate with the sink node, there are two possibilities. When the wrist is at the back of the body, non line of sight (NLOS) communication is considered where the sensor node will send data to the relay node and then the sink node. Whereas, in cases where the wrist is in the front, line of sight (LOS) communication exists between the sensor node and sink. The data measure through these sensor nodes needs to be periodically sent to an external server through the sink. The probability for LOS and NLOS communication is considered 0.5 and 0.5.

Once a node wants to send data through LOS communication it sends a Request to Send (RTS) signal with a power level that only nodes in its LOS can receive it. The nodes in LOS position will reply by sending an ACK (Acknowledge) signal in a specified time slot. The sender node will now be able to directly send its packet to the node in its LOS position. In cases where no node exists in the LOS position of the sender node the RTS signal will not be received and no ACK signal will be sent in the time out interval. After the timeout period a wakeup signal will be sent to identify when the node is ready to start the communication. In the end of the communication, a Receive Acknowledge (RAck) signal will be sent to the sender node to announce successful communication. In cases where the RAck signal is not received, the mentioned procedure will be repeated.

The proposed opportunistic routing scheme aims to increase network lifetime and is compared to one-hop or two-hop communication and shown to have the same energy consumption for multihop transmission in the sensor node but has approximately half the energy consumption of multihop communication at the relay node. The results have shown the capability of decreasing energy consumption to increase network lifetime in the relay and sensor via preserving the same Bit Error (BER) of one-hop and two-hop communication. Moreover, the energy consumption of the relay nodes have shown to decrease dramatically via the proposed opportunistic scheme which leads to overall decrease in overhead energy consumption as relay nodes are major consumers of overhead in the network.

The overall energy consumption of the proposed routing algorithm lies in between one-hop and multihop communication where multihop communication costs double the energy of one hop. However, this protocol does not consider the energy level of nodes and is not scalable due to increase of traffic on the relay node from an increase in the overall number of nodes.

B. Prediction-based Secure and Reliable routing (PSR)

Liang et. al [35] have proposed the distributed (PSR) routing framework for BANs where each node n_i maintains the matrix M_i $(s \times p)$ which stores the link quality measurements between itself and all other nodes in the network during the past p time slots (p is a predefined parameter and the initial matrix is empty). Each row belongs to a unique node where the k-th column corresponds to the link quality between n_i and other nodes in $T_{c-p+k-1}$ (T_c is the current time slot). Link quality is determined through the received signal at the receiver side. The values of the matrix at two time slots T_c and T_{c+1} are shown in Fig. 8. n_i generates an order-p auto-regressive model through which node n_i is capable of predicting its link quality at time T_c with every other node and picks a node closer to the sink with better link quality. Data transmission of node n_i is heard by all neighboring nodes where the received signal power is measured. Then, an ACK consisting of their intention to be a receiver or not is replied to n_i through which M_i is updated. However, this protocol is not scalable and is only suitable for BAN applications with few number of nodes due to the huge overhead for maintaining the table.

$\mathcal{M}_i$ at the beginning of time slot T_{c+1}

	T_{c-p}	T_{c-p+1}	⋯	T_{c-1}	T_c
n_0	$q_{i,0}(c-p)$	$q_{i,0}(c-p+1)$	⋯	$q_{i,0}(c-1)$	$q_{i,0}(c)$
⋯	⋯	⋯	⋯	⋯	⋯
n_{i-1}	$q_{i,i-1}(c-p)$	$q_{i,i-1s}(c-p+1)$	⋯	$q_{i,i-1}(c-1)$	$q_{i,i-1}(c)$
n_{i+1}	$q_{i,i+1}(c-p)$	$q_{i,i+1}(c-p+1)$	⋯	$q_{i,i+1}(c-1)$	$q_{i,i+1}(c)$
⋯	⋯	⋯	⋯	⋯	⋯
n_s	$q_{i,s}(c-p)$	$q_{i,s}(c-p+1)$	⋯	$q_{i,s}(c-1)$	$q_{i,s}(c)$

$\mathcal{M}_i$ at the beginning of time slot T_c

Fig. 8. Link quality matrix M_i of node n_i [35]

C. Probabilistic routing with postural link costs (PRPLC)

PRPLC [36] sets a Link Likelihood Factor (LLF) namely P^t_{ij} $(0 \leq P^t_{ij} \leq 1)$ which denotes the likelihood for link L_{ij} between node i and j to be connected over a discrete time slot t. LLF is determined to be dynamically updated after the tth time slot as follows:

$$P^t_{ij} = \begin{cases} P^{t-1}_{ij} + (1 - P^{t-1}_{i,j})\omega & \text{if } L_{ij} \text{ is connected} \\ P^{t-1}_{ij}\omega & \text{if } L_{ij} \text{ is disconnected} \end{cases}$$

When the link is connected, P^t_{ij} is determined to increase with a constant rate ω plus the difference of its maximum value which is 1 and its current value, P^t_{ij}. For low values of ω, P^t_{ij} rises slowly when the link is connected and degrades fast when the link is not connected. On the other hand, for high values of ω, P^t_{ij} rises fast when the link is connected and degrades slowly when the link is not connected. P^t_{ij} is expected to rise fast and degrade slowly for a historically good link and to rise slow and degrade fast for a historically bad link. Hence, ω should be capable of gaining knowledge of a long-term history of the link which is described through the definition of Historical Connectivity Quality (HCQ) for an on-body link L_{ij} in (8) as follows:

$$\omega^t_{i,j} = \sum_{r=t-T_{window}}^{t} \frac{L^r_{i,j}}{T_{window}} \tag{8}$$

where T_{window} is the measurement window (number of slots) over which the connectivity quality is averaged. L_{ij} is 0 if the link is not connected over time slot r, and 1 when the link is connected. All nodes observe and maintain their LLF to be in one-hop contact with each other at all times. The aim of PRPLC is to choose high link-likelihoods to reduce end-to-end delay and intermediate storage delay relative to packets getting stuck at nodes with low link likelihood.

When a node i wants to route data to a node d (sink node) and meets node j, node i forwards the packet to node j if and only if $P^t_{i,d} \leq P^t_{j,d}$ is valid. More specifically, in such cases node j is more likely to meet node i as it has a higher link likelihood which explains the reduction in end-to-end delay via transferring a packet from node i to node j. Also, each node updates its P^t_{ij} values with all nodes in the network through its periodic *Hello* messages which are also used to send the P^t_{id} values with the common destination node d.

In cases where packets are stored in node-i's buffer, node-i finds out if there is a node that has a higher LLF to node d . In cases where there is a node with a higher LLF to the destination node, packets are forwarded to that node. Otherwise, node-i continues to store its packet in its own buffer if it has the highest LLF to the destination node.

TABLE II
COMPARISON OF COST-EFFECTIVE ROUTING PROTOCOLS IN BANS

Characteristics	Cost-effective Routing					
	Opportunistic Routing	PRPLC	DVRPLC	OBSFR	PSR	ETPA
Delay	Low	High	High	Low	High	High
Network Lifetime	High	High	High	Low	Low	High
Link Probability	LOS and NLOS	✓	✓	✓	✓	✓
PDR	100%	up to 88%	up to 89%	up to 92%	up to 80%	up to 95%
GPS	✓	×	×	×	×	×
Mobility	✓	✓	✓	✓	✓	✓
Energy Usage	Low	Low	Low	High	High	Low

D. Distance vector routing with postural link costs (DVR-PLC)

DVRPLC [16] proposes that all nodes preserve the cumulative path cost to the common sink node. As with PRPLC, this protocol chooses high likelihood paths to decrease end-to-end packet delivery delay and decrease intermediate storage delay relative to storing packets at nodes with low link likelihood. DVRPLC specifies a Link Cost Factor (LCF) of $C_{ij}^t (0 \leq C_{ij}^t \leq C_{max})$ which stands for the routing cost of link L_{ij} in a discrete time slot t. LCF is defined to be updated dynamically after the *t*th time slot as follows:

$$C_{ij}^t = \begin{cases} C_{ij}^{t-1}(1-\omega_{i,j}^t) & \text{if } L_{ij} \text{ is connected} \\ \omega_{ij}^t(C_{ij}^{t-1}-1)+1 & \text{if } L_{ij} \text{ is disconnected} \end{cases}$$

C_{ij}^t decreases at a fixed rate of $(1-\omega_{i,j}^t)$ where $\omega_{i,j}^t (0 \leq \omega_{i,j}^t \leq 1)$ is the HCQ described in (8). As in PRPLC, both short and long term link localities are shown to minimize delay with the same routing procedure with the difference of choosing links of lower costs. DVRPLC aims to minimize end-to-end cumulative cost which outperforms PRPLC that has considered LLF to only be in the link level.

E. On-Body Store and Forward Routing (OBSFR)

OBSFR [37] attempts to avoid network partitioning which may arise by allowing each node to maintain its *source_id, seq_No* and list of *node-ids* that demonstrate its path so far from the source node. Hence, once a packet arrives at a node for the first time, the node continues to store the packet until it meets at least one node that is not listed in the *node-ids* of the packet. In such cases, node i broadcasts the packet to the node it has encountered and deletes the packet from its buffer. As in regular flooding, node i will ignore the reception of the same packet. However, this routing scheme is only applicable to small networks of few nodes and not scalable to large networks due to the requirement of tens of *ids* being added to the packets.

OBSFR has shown to have a packet delivery ratio of up to 92 % which is due to multi-packet forwarding that leads to lower packet loss. However, there is a unique type of packet loss in OBSFR relative to *partition packet saturation*. Also, OBSFR and DVRPLC have been shown to have higher packet hop count leading to longer routes compared to PRPLC.

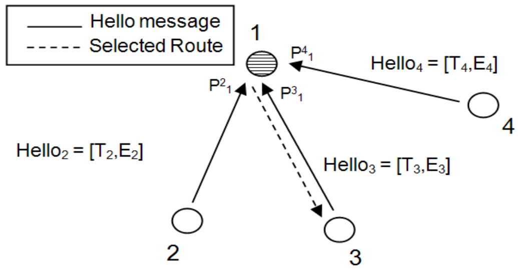

Fig. 9. Route Allocation in ETPA

F. Energy Efficient Thermal and Power Aware (ETPA) Routing

Movassaghi et. al [38] have proposed an energy efficient, thermal and power aware routing algorithm for BANs named Energy Efficient Thermal and Power Aware routing (ETPA). This protocol calculates a cost function for route allocation based on a nodes temperature, energy level and received power from adjacent nodes. In order to avoid idle listening and decrease interference, the frames are considered to be divided into time slots by the number of nodes in the network, N, where each node is allowed to transmit in the time slot it has been assigned (i.e TDMA). In each cycle (every four frames), each node, j, broadcasts its temperature, T_j and its available energy level, E_j, through a *HELLO* message in its allocated time slot to all its adjacent nodes. Next, each node estimates the received power from its adjacent nodes (Fig. 9). Hence node i becomes capable of calculating the cost of transmission to node j through (9) as follows:

$$C_{i,j} = \alpha_1\left(\frac{P_m - P_i^j}{P_m}\right) + \alpha_2\left(\frac{T_j}{T_m}\right) + \alpha_3\left(\frac{E_m - E_j}{E_m}\right) \quad (9)$$

where α_1, α_2 and α_3 are non-negative coefficients, P_i^j is the received power at node i from node j, P_m is the maximum received power at each nodes, E_m is the maximum available energy at each nodes and T_m is the maximum temperature allowed. In the next frame, each node which has a packet to send, finds the node with minimum cost and forwards the packet to that node. Otherwise, the packet is stored at the node itself. For example in Fig. 9, $C_{1,3}$ is less than $C_{1,2}$ and $C_{1,4}$, so, node 3 is selected as the next node. Also, packets that have been stored for more than 2 frames are considered to be dropped.

ETPA has shown to significantly decrease temperature rise and power consumption and provide a more efficient usage of the available resources. Additionally, it has a considerably high depletion time that guarantees a longer lasting communication among nodes.

A comparison of the cost-effective routing protocols in BANs is provided in Table II. As in all cost-effective protocols, the cost-effective relation between all nodes needs to be periodically updated and stored, a large amount of transmissions and overhead is required to find routes which also adds complexity to the system.

VIII. QoS BASED ROUTING

A. LOCALMOR

A novel QoS-based routing protocol has been proposed in [39] for biomedical applications of sensor networks via traffic diversity namely LOCALMOR. The proposed protocol functions in a localized, distributed, computation and memory efficient way. It also classifies data traffic into several categories based on the required QoS metrics where different techniques and routing metrics are provided for each category. LOCALMOR deploys diversity of data traffic whilst considering reliability, latency and residual energy in sensor nodes and transmission power between sensor nodes as QoS metrics of the multi-objective issue. Additionally, the proposed protocol can be used with any MAC protocol if an ACK mechanism is employed.

Four modules exist in the proposed protocol as it follows a modular approach explained in the following:

- *Delay-sensitive Module:* This module deals with routing packets that are required to be delivered by a given deadline. It deploys the packet velocity approach provided in [40] that does not require any synchronization amongst the nodes.
- *Power-efficiency Module:* This module handles regular packets and can be used by other modules in cases where the required data-related metrics need to be optimized by several nodes.
- *Reliability-sensitive Module:* This module deals with routing packets requiring high reliability to enhance the chances of delivering a packet by sending a copy to both the primary and secondary sinks. Thus, a multi-sink single path is chosen instead of a single-sink multipath approach which leads to convergence of data packets close by or at the sink and results in increase of collision and traffic congestion.
- *Neighbor Manager:* This module executes HELLO messages, implements estimation methods, manages neighbor tables and provides other modules with their expected information based on their packet type.

However, scalability has not been investigated in the proposed protocol and a high number of nodes need to be configured as well as a real sensor network using motes.

B. Data-centric Multi-objective QoS-aware routing (DMQoS)

Razzaque et. al [41] have proposed a data-centric multi-objective QoS-aware routing protocol, namely DMQoS, for delay and reliability domains in BANs. The proposed protocol provides customized QoS services for each traffic category based on their generated data types. It employs a modular design architecture that consists of different units that operate in coordination with each other to support multiple QoS services. More specifically, it consists of the following five modules:

- *Reliability Control:* Reliable data delivery to the destination can be effected via link/node failure, congestion, node mobility, link quality degradation, etc. This module uses the greedy approach for its reliability control algorithm. First, a candidate downstream node j is identified at each node i for each sink $s \in S$ with maximum reliability $r_{i,j}$ and stores it in the NH_r variable. The packet is immediately dropped in cases where NH_r returns a Null. In cases where only one node is returned, the packet will be forwarded to the next hop if its reliability is higher than the required reliability R and dropped otherwise.
- *Delay Control:* This module controls on-time delivery for time critical emergency packets where the life-time of a packet (t_{life}) bounds the maximum allowable latency for delay-guaranteed service required by the application. The end-to-end packet latency at the network layer is the sum of the propagation delay, queuing delay, processing delay and transmission delay where the queuing delay has the most significant amount of the latency followed by the transmission delay.
- *QoS-aware Queuing and Scheduling Modules:* This module considers four individual queues in a sensor node where the highest priority is given to critical packets (CP), the second highest probability is given to delay-constrained packets (DP), the third priority is for reliability-constrained packets (RP) and the least priority is given to ordinary packets (OP).
- *The Dynamic Packet Classifier:* This module defines four separate classes of packets as follow: ordinary packets (OP), critical packets (CP), delay-constrained packets (DP), reliability-constrained packets (RP),
- *Energy-aware Geographic Forwarding (EAGF):* This module deploys a localized packet forwarding that uses hop-by-hop routing instead of traditional end-to-end path discovery routing. Thus, a packet will have numerous choices in choosing a path to the destination. The aim is to choose a downstream node with higher geographic progress and higher residual energy towards the destination where the first approach leads to lower number of hop between the source and destination and the second one provides a balance of energy consumption amongst the potential downstream nodes. This tradeoff is further managed

via the multiobjective Lexicographic Optimization (LO) approach.

Additionally, a homogenous energy dissipation rate is ensured for all routing nodes in the network using a multiobjective Lexicographic Optimization-based geographic forwarding that uses a localized hop-by-hop routing based on the QoS performance and geographic locations of the neighbor nodes.

In summary, DMQoS provides a better performance compared to LOCALMOR in terms of end-to-end delay and packet delivery ratio.

C. Reinforcement Learning Based Routing Protocol with QoS support (RL-QRP)

A reinforcement learning based routing protocol with QoS support (RL-QRP) has been proposed in [42] which uses the basic idea of location information where sensor nodes can of compute the available QoS routes based on the link qualities of the available routes and the QoS requirements of the data packet, and forward data packets to one of the neighbor nodes. This procedure is continued in forwarding the data packets to the sink node and iterates at each relaying node till the packets reach the sink node. Thus, a distributed reinforcement learning algorithm is used for the computation and selection of the QoS routes where each of the sensor nodes individually and graphically calculate the route.

The major issue with shortest path routing, geographic routing and other pre-defined routing protocols are relative to congestion avoidance and network load balance. More specifically, in these networks a sensor nodes forwards its data packets to nodes that are geographically closer to the sink without considering their communication and computation load, duty cycle, their buffer status, etc. This challenge is taken into consideration with the design of adaptive QoS routes that considers neighbor nodes' state information, and link quality. But, the prediction and maintenance of such information in highly dynamic environments is quite challenging. Thus, the RL-QRP algorithm uses the independent distributed reinforcement learning (IndRL) approach for QoS route calculation where a sensor node does not consider the interaction among itself and other sensor nodes and only considers itself capable of changing the state of the environment. However, the proposed approach is not efficient for global optimization in large scale networks.

D. QoS framework

Liang et. al [43] have proposed a QoS-aware routing protocol for biomedical sensor networks with the aim of providing differential QoS support and prioritized routing service in the network . This procedure is accomplished via the following tasks: establishment and maintenance of QoS-aware routes, prioritized packet routing, feedback on network conditions to user application, adaptive network traffic balance and Application Programming Interfaces (API). The routing module is in charge of route maintenance and establishment through proactive table-driven algorithms where each node preserves its routing information to the sink node and stores all possible routes to the sink in its routing table by indexing the node IDs of its one-hop neighbors. In the route setup phase, the sink node indicates its existence by sending broadcast sink advertisement (ADV) packets. These packets are received and stored by sensor nodes in the communication range of the sink node. Next, the sensor nodes broadcast Route Information (RI) packets to its neighbor nodes indicating they can be used as routers to the sink node. The neighbor nodes will also set up their own routing tables and broadcast RI packets to their neighbors. Therefore, all sensor nodes will establish a path to the sink nodes after a while.

Due to topological changes relative to change in the wireless channel and node or link failure, network information needs to be periodically updated. The sink nodes broadcast ADV packets in a fixed period. All sensor nodes check route information in the packet upon receiving a ADV or RI packet, update their routing tables and broadcast RI packets accordingly. Additionally, the proposed QoS framework provides prioritized packet routing by providing a classification for all the packets including data packets and control packets.

IX. Routing in BANs vs. Others

Energy consumption and network lifetime are two of the major challenges in BANs as recharging and replacing batteries of devices attached to a human body may lead to one's discomfort. Moreover, the surrounding area of the human body is considered as a lossy medium for data communication. Hence, electromagnetic waves around the body are considerably attenuated leading to high data path loss and delay spread due to placement on different body sides and constraining data transmission over an arbitrary distance around the body. In cases with too much data transmission around the body, temperature rise and tissue heating can cause significant issues [44].

Literature has shown many power-aware and QoS-aware routing protocols described for WSNs, MANETs which are not applicable to in-body and on-body BANs given their stringent constraints. Much of the research in MANETs has focused on improving scalability[45–47], whereas in BANs currently its more about energy efficiency. More specifically, power dissipation and communication radiation of implanted sensors may lead to severe health hazards [19, 48]. QoS is important in many BAN applications such as artificial retinas and in other applications large delays could be fatal. Therefore BAN routing protocols need to ensure they can address the QoS constraints of the respective applications [1]. Hence, the routing protocols designed for BANs must also consider the delay specifications in communication of the sensed data to the base-station [20].

A number of energy efficient routing protocols have been proposed for MANETs that aim to find routes that minimize energy consumption in terminals with little energy resources and ignore the load of operations in memory access, data processing, measurement and also the required energy to receive or transmit data over a wireless link [4]. Moreover, the loss of a device or sensor is not considered an issue [5].

Routing protocols designed for WSNs mainly focus on delay constraints and energy-efficiency whereas not considering the effects of power dissipation and communication radiation of the implanted sensors. Two types of hotspot routing issues have been stated to exist in the networking field, namely, *link hot spot* and *area hot spot* [19]. Area hot spot refers to the entire region around a node as hot and all of its surrounding links to be disconnected which leads to node isolation. Link hot spot refers to disconnection of a link. However, the proposed sensor network and ad hoc routing protocols mainly focus on link hot spot whereas other links of the node may be available [19].

Heterogenous devices are required in BANs with different data rates, whereas WSNs consider homogenous sensors throughout the network. However, some applications in BANs support non-real time data communication. The mobility pattern in BANs changes in the order of movements within tens of centimeters whereas the scale of mobility in WSNs is in the order of meters and tens of meters [5]. In WSNs, traffic flow is amongst the sensors and their sinks and between any two pair of nodes in MANETs.

X. Conclusion and Future Directions

We have classified routing protocols in BANs into five categories: temperature based, cluster-based, cross layer, cost-effective and QoS-based. We have described the design and constraints of the individual routing protocols with respect to their category and their application in BANs. The temperature-based routing protocols used for in-body BANs only consider temperature as a metric for choice of routes that would either avoid hot regions or detour after reaching a hot region. The cost-effective routing protocols calculate a probability for a link to be connected based on knowledge from certain characteristics in the network. However, none of the cost-effective routing protocols consider temperature rise in the nodes and the path loss among sensor nodes around the body. The cluster based and cross layer routing protocols are mainly reactive and need to gain knowledge of the connectivity of all nodes in the network and their other features which leads to significant overhead. QoS-based routing protocols aim to accomplish the required QoS metrics.

Some of the challenges of routing in BANs are considered in different categories of routing protocols proposed but still a lot more work needs to be done. The proposed routing protocols either do not consider postural body movements with mobility or are not as energy efficient. Also, most of the aforementioned routing protocols have not considered reliability and QoS. The future vision of BANs is to provide energy efficient and reliable communication among sensors in both real-time and non real-time applications. Also, more accurate propagation models are required that consider mobility, latency, reliability, mutual interference and energy consumption that construct a more efficient architecture for better routing protocols in BANs.

Future routing protocols for BANs should be capable of obtaining the required QoS as well as maintaining a well balanced low power energy consumption. This can be achieved by jointly designing the MAC layer and the routing protocol in order to satisfy both energy and QoS requirements. Such a procedure can be found in the excessive body of research in the field of WSNs and MANETS that should be considered to be used in BANs. However, these protocols need to be modified and optimized to be efficiently used in BANs.

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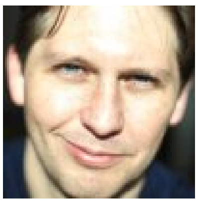

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