Designing 2-Hop Interference Aware Energy Efficient Routing (HIER) Protocol for Wireless Body Area Networks

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Abstract. With the evolution of wireless communication and advent of low power, miniaturized, intelligent computing devices, sensor network technology initiates the era of Wireless Body Area Network (WBAN) for medical applications. This new trend of healthcare empowers continuous supervision of vital physiological parameters under free living conditions. However, the potency of WBAN applications are subject to reliable data delivery. Inherent challenges of WBAN such as scarce energy resource, varying link quality, propensity of tissue damage necessitate optimal routing strategy to combat with hostilities. In addition, coexistence of multiple WBANs within proximity results in severe degradation of throughput as well. In this paper, a cost-based energy efficient routing protocol has been designed which ensures satisfactory performance without fostering thermal effect and adapts itself in adverse situations like intra BAN as well as inter BAN interference. The performance of the proposed algorithm is analyzed through comprehensive simulations. The protocol is analyzed for different mobility models signifying relative body movement due to posture change. The simulation results demonstrate that our proposed protocol out performs other protocols with respect to energy efficiency while maintaining a stable packet delivery ratio under interference.

Keywords: WBAN · Routing · Intra BAN interference · Inter BAN interference

1 Introduction

Application of sensor network technology in human health monitoring has revolutionized the conventional concept of health care. The new era of proactive health monitoring involves collection of light-weight, small-size, ultra-low powered, intelligent micro or nano technology bio sensors to be placed in, on or around human body to monitor vital physiological parameters [1]. Consequently,

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Wireless Body Area Network (WBAN) is formed to transmit the acquired data to a remote server via network coordinator for real time diagnosis by medical personnel as depicted in Fig. 1. These devices are generally powered by batteries with bounded lifetime [2]. Hence, to acquire everlasting welfare of WBAN applications network lifetime should be enhanced which necessitates the use of ultra low power transceiver as well as power efficient MAC protocol for intra BAN communication. On top of that, designing energy efficient protocol [3] for network layer communication alleviate preservation of this scarce resource to a greater extent. Mostly, sensor nodes in WBAN follow star topology [1] where the network co-ordinator resides at the center. Intra-BAN communication can be done using Bluetooth (IEEE 802.15.1), ZigBee (IEEE 802.15.4) or IEEE 802.15.6 standard (mainly for implantable nodes). However, to bring down the power expenditure due to direct (single hop) communication between source and sink, multi-hop communication is often preferred. The latest version of the IEEE standard proposed for WBANs in February 2012 recommends at most two hops for IEEE WBAN standards compliant communication [2]. However, more than two hops could be exploited by the proprietary systems with the cost for handling inter-operability issue. The bio-sensor nodes are in direct contact with human body; thus the absorption of electromagnetic radiation by human body causes imprudent temperature rise of human tissue [4] leading to several health hazards [1,5] such as reduced blood flow, tissue damage, enzymatic disorder etc. The amount of radiation absorbed in human body is measured in terms of Specific Absorption Rate (SAR) [6]. Designing network protocol for WBAN must ensure reliable data delivery with least thermal impact. Repeated participation in network activities could cause rate capacity effect [3] leading to prompt energy depletion. Furthermore, posture change may result in relative node movement in WBAN which imposes difficulties in choosing the optimal transmission power subject to varying link quality. In addition, link degradation due to channel fading increases packet error rate and overall network performance is affected as well; the case is worse when multiple WBAN coexist within a small region.

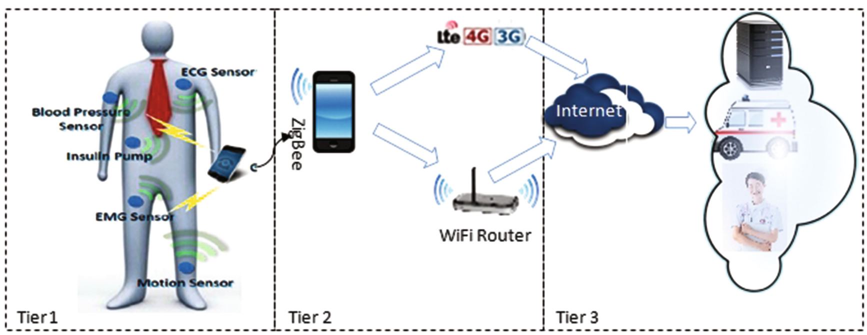


Fig. 1. 3-tier network architecture of WBAN

The existing routing protocols contemplate predominantly one or more of these issues, however, optimal solution is still indispensable. Thermal aware protocols such as [3,4] mostly go for multi-hop communication to prevent temperature upswing of individual nodes, however, that may not result in energy efficient routing. Besides, additional overhead like delay could be imposed as well. Interference aware protocols [7,8] emphasize on hindering throughput degradation due to co-existing communicating nodes, inherent challenges are yet to be incorporated into the solutions. Accordingly, a 2-Hop Interference aware Energy efficient Routing protocol (HIER) has been proposed in this work. This work is the extended version of the work presented in [9]. In this work, our contributions are as follow: The protocol exhibits adaptive routing strategy in situations like intra BAN interference and inter BAN interference; it omits acknowledgment policy as regarded in [9] to bring down energy expenditure and control packets overhead; a detailed study has been carried out in performance evaluation subject to different mobility models.

The paper is organized as follows: State of the art works on BAN routing protocols are presented in the next section. Section 3 gives detailed description of our proposed routing protocol. Experimental setup and simulation results are discussed in Sect. 4. Finally, Sect. 5 concludes.

2 Related Work

The trends in existing researches on WBAN routing protocols are organized according to time-line in Table 1. Existing routing protocols are grouped into six categories focusing on their objective in solving routing problems. In earlier days researches were focused towards addressing a specific issue of BAN routing such as temperature control [3,4], clustering [10,11]. However, the trend does not go far due to some inherent limitations associated with it. Thermal aware routing [3,4] often fails to resolve other major issues such as energy efficiency, reliability. In addition, cluster based routing protocols [10,11] group the nodes in WBAN into clusters and each cluster is supervised by a cluster head. Data communication between sensor nodes of a cluster and sink is governed by the respective cluster head. However, periodic cluster formation and cluster head selection cause significant overhead for a network of 15 to 20 nodes i.e. the average network size in case of WBAN [1].

Herewith, researches move towards addressing multiple issues which are often cross layer [14,15] or furnish modules for different QoS parameters [16,21]. Cross layer protocols combine the routing layer challenges with medium access issues. Time is divided into slots and nodes reserve slots prior to actual data transfer as in [14,15]. Protocols in this category enhance collision free data transfer, hence throughput increases. To foster energy use up, nodes turn off their transceiver when not required. However, these protocols are not well suited subject to substantial body movement. In QoS based routing protocols data traffic is divided into several categories as in [16,21] based on QoS requirements and separate modules are devised to meet with desired criteria. Although these protocols

Table 1. Timeline of existing routing protocols

Year	Temperature based protocols	Cluster based protocols	Cross layer protocols	Cost effective protocols	QoS based protocols	Interference aware protocols
2004		[12]				
2005	[4]	[13]				
2006	[3]		[14]			
2007	[5]	[10]	[15]		[16]	[17]
2008	[18,19]		[20]		[21]	
2009	[22]		[23]	[24,25]	[26]	[27]
2010				[28]		[29]
2011				[30]	[31]	[7]
2012				[32,33]		
2013		[11]		[34,35]	[36]	
2014					[37]	[8,38,39]
2015				[41–43]		
2016			[40]	[44]		
2017				[9]		

enhance throughput as well as reliability with low end-to-end delay, the system overhead increases to a large extent for designing several modules for QoS metric. In addition, another trend in designing routing solutions for WBAN is to address interference issue [8,38]. Hitherto strategies are devised to oversee intra BAN interference issue as in [17,29]. However, WBAN yields constant medical supervision under free living condition leading to potential interference with coexisting WBANs as well. Accordingly, researches [7,8] move towards perceiving solutions to combat with inter BAN interference complications. To cope up with interference issue a system is designed prior to adopting routing protocol to operate in that framework [8,17]. But this trend is yet to be explored more and a compact policy is still required to overcome intra BAN as well as inter BAN interference along with inherent challenges of WBAN routing.

Consequently, the trend moves towards cost based routing [24,25] where the major issues of BAN routing such as temperature control, link quality, energy efficiency, mobility are considered in cost calculation and a trade off is made. Data is routed through the least cost route. However, cost evaluation process is either centralized or distributed. In case of centralized cost computation as in [34,41,42], sink acquires relevant information of other sensors such as remaining energy, distance from sink etc. and formulates costs for each node and these costs are exploited during data forwarding. Unlike centralized approach, in distributed cost assessment [32,33] each node evaluates cost for its neighbors relies on multiple criteria such as remaining energy, link quality, temperature etc. and opts for suitable least cost relay node for data forwarding. However, the centralized cost evaluations are subject to the energy expenditure due to periodical exchange of node information with sink. Nodes in WBAN often choose forwarder opportunistically in case of intermittent network connections [28,30] and data is routed in store, carry, forward modes. Cost based protocols in WBAN mostly select least cost relay for data forwarding; however few approaches [28] take into account cumulative path cost to the sink node leading to less intermediate storage delay but intensify the overhead of caching cumulative path cost. Herewith, a cost based 2 hop energy efficient routing protocol has been designed in [9] where distinct sources of energy consumption in WBAN and its effect in human body and communication system as well as the network are analyzed and incorporated in routing decision. Authors demonstrated that more energy consumption by the body sensors may improve performance of a particular link but it affects both the human body and the network in many ways (shown in Fig. 2). The protocol in [9] selects forwarder considering issues such as remaining energy, link reliability, node reliability. Besides, increase in Specific Absorption Rate (SAR) of the forwarder resulting from relaying data is also contemplated in relay selection. As shown in Fig. 2, most of the routing protocols incorporate one or more of the existing issues like increase in SAR or link reliability etc. In [9], the authors have dealt with some combination of issues. In this work the protocol in [9] is extended to handle the effect of intra BAN and inter BAN interference in routing.

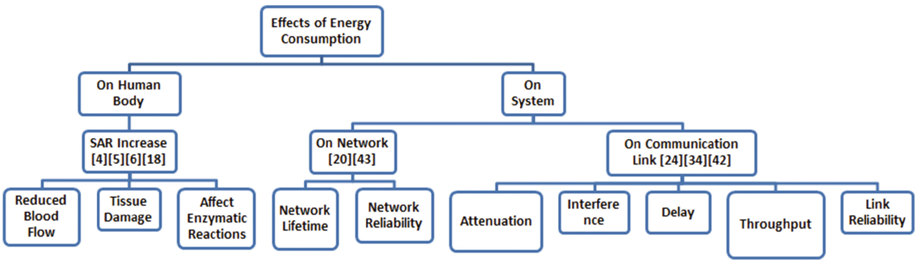


Fig. 2. Effect of energy consumption of body sensors both on human body and on system as in [9]

3 Proposed Work

Existing researches exhibit the major issues of WBAN and how these exert influence on routing. Our protocol has been devised to address the issues as presented in previous sections. A brief description of the proposed algorithm is as follows.

Any node i in the network that wants to communicate its data to the sink broadcasts $SETUP\_REQ$ in one hop neighborhood with substantially low transmission power. The node may receive $SETUP\_RES$ from either sink or those neighbors which has direct connectivity with the sink. Here the communication is restricted within 2 hops i.e. either from source to sink (1 hop) or from source to relay plus relay to sink (2 hops). On receiving reply from sink, the node communicates its data directly to the sink. Besides, if the rate of energy depletion at node i is less, then node i may act as potential relay for others. Since the node is capable of communicating with the sink at low transmission power, the energy consumption as well as SAR reduces even if working as relay. The nodes that do not receive $SETUP\_RES$ from sink s, may check whether they have received any $SETUP\_RES$ from neighbors and evaluate fitness $F^j(t)$ of each neighbor j to act as relay in terms of energy ratio $ER^j(t)$, link reliability $R_{(i,j)}(t)$ and SAR ratio $SARRatio^j(t)$ defined in Eqs. 3, 4 and 6 respectively. If there remains any node that does not receive $SETUP\_RES$ from either sink or relays, it attempts to communicate with enhanced transmission power. Whenever communicating with sink as well as neighbors node i observes for sudden degradation of Signal to Noise Ratio (SNR) which may result due to intra ban as well as inter ban interference and behaves accordingly.

System model: The network consists of N sensor nodes, and each node can act as source as well as relay. In this work we have considered single sink node which performs as network coordinator although the proposed approach may be applied to multiple sink scenario as well. Every node in the network carries out transmissions with uniform transmission power P_{tx}. The bio-sensor nodes communicate with each other through electro-magnetic radio frequency waves. The radiation absorbed in human body is quantified in terms of SAR. SAR is quantified subject to the distance 'R' from the sensor node position; if the reference point is located in the near field region of the source node, SAR is quantified as follows [6]

$$SAR = \frac{\sigma}{\rho}\frac{\mu\omega}{\sqrt{\sigma^2+\epsilon^2\omega^2}}(\frac{Idlsin\theta}{4\pi}e^{-\alpha R}(\frac{1}{R^2}+\frac{|\gamma|}{R}))^2 \tag{1}$$

Here σ, ϵ, μ represent conductivity (S/m), permittivity (F/m) and permeability (H/m) of the medium respectively. γ is the complex propagation constant and complex intrinsic impedance $\eta = \frac{\gamma}{\alpha+j\omega\epsilon}$ at frequency ω. dl is the dipole length and current I is uniform and varies sinusoidally with time. Likewise, if the reference point is located at far field region of the source node, SAR is computed as follows [6]

$$SAR = \frac{\sigma}{\rho}(|\eta||\gamma|\frac{Idlsin\theta}{4\pi R}e^{-\alpha R})^2 \tag{2}$$

In addition, at any point of time t each node i measures its own energy ratio ($ER^i(t)$) as follows [9]

$$ER^i(t) = \frac{E^i_{rem}(t)}{E^i_{ini}} \tag{3}$$

This ratio is a prerequisite for relay selection process. It is evident that a node with more remaining energy is more eligible to act as relay.

Following is the details of the proposed algorithm (Algorithm 1).

In a network of N nodes, a node i initiates the algorithm when it has data for sink in other words, the protocol operates on demand. The algorithm works in two phases. During setup phase node i exchanges SETUP packets with neighbors to identify its connectivity with sink as well as other nodes and this is followed by data transfer phase. A node acquires neighbor information in setup phase. Setup phase is initiated when node i broadcasts $SETUP\_REQ^i$ in one hop neighborhood. The transmission is conducted with substantially low transmission power. The aim is to discern whether sink is reachable even at this low power level. This has both way benefits: if sink is reachable then subsequent communications could be made directly to the sink with such low transmission power which may not lead to excessive temperature rise of human tissue; besides the node may participate in data relaying for others as well without much energy depletion. Node i confirms direct connectivity to the sink s when it receives $SETUP\_RES^s$ from sink. At this point, node i may broadcast itself as potential relay if its energy depletion rate $(\frac{E_{rem}(t-\Delta t)-E_{rem}(t)}{\Delta t})_i$ is within pre-specified limit $E_{threshold}$. However, node i may receive $SETUP\_RES^j$ from neighbor j as well if neighbor j has direct connectivity with sink. Neighbor j includes its energy ratio ER^j quantified following Eq. 3 along with $SETUP\_RES^j$ for i. However, if node i does not receive $SETUP\_RES^s$ from sink, it looks for $\forall j \in k$ $SETUP\_RES^j$ received from k neighbors. Node i also observes the Received Signal Strength Indicator (RSSI) and evaluates reliability $\forall j \in k$ $R_{(i,j)}(t)$ of the link between node i and each neighbor j as follows [9]

$$R_{(i,j)}(t) = \frac{RSSI_{avg}^{(i,j)}(t)}{RSSI_{max}^{(i,j)}} \tag{4}$$

The link reliability evaluation reflects potential existence of the link over time subject to its maximum quality instead of just considering a single scenario. Node i caches the information received during setup phase for certain time in routing table RT_i so that a number of data packets may be sent without setup overhead. After the time period is over, node i again initiates setup phase if it has more data for the sink. However, each node in WBAN is provided with limited storage capacity. Thus if buffer exceeds, the node i discards information of the neighbor j with comparatively low energy ratio $ER^j(t)$. Accordingly, node i enters into the data transfer phase which includes forwarder selection process in case sink does not reside in one hop neighborhood. In such case node i computes fitness $\forall j \in k$ $F^j(t)$ of k neighbors to identify suitable forwarder. In addition to energy ratio ER^j and link reliability $R_{(i,j)}(t)$, increase in SAR in neighbor j to act as relay is also assessed by node i as a parameter for fitness calculation. Authors have analyzed in [9] how SAR is related to the transmission power (P_{tx}) given other parameters of Eq. 1 remain constant. Node i predicts increase in SAR at neighbor j to relay q bits data with transmission power P_{tx} as [9]

$$SAR^j = m \times q \times P_{tx} \tag{5}$$

Here m is constant relies on the network conditions. With this, node i evaluates $SARRatio^j(t)$ as follows [9]

$$SARRatio^j(t) = \frac{SAR^j(t)}{SAR_{Lim}} \tag{6}$$

Here SAR_{Lim} is retained much less as compared to its regulatory limit 1.6 W/Kg [1] assuming the node j is engaged in other activities as well apart from data relaying. $SARRatio^j(t)$ is updated after relaying each data packet accordingly. Hereafter, node i finally computes fitness $\forall j \in k$ $F^j(t)$ as follows [9]

$$F^j(t) = w_1 ER^j(t) + w_2 R_{(i,j)}(t) + w_3(1 - SARRatio^j(t)) \tag{7}$$

A neighbor with maximum fitness value is selected as potential forwarder to relay data to sink. Fitness of a neighbor is assessed contemplating energy ratio ER^j, link reliability $R_{(i,j)}$ and $SARRatio^j$ and each metric is weighted accordingly such that $w_1 + w_2 + w_3 = 1$. Value for these weights are chosen empirically such that the prime objective of this protocol is reflected in decision process.

Unlike energy ratio ER^j and link reliability $R_{(i,j)}$, $SARRatio^j$ has negative impact on fitness calculation. This metric regulates the distribution of forwarding traffic among potential relays such that the most suitable relay does not get overburdened with forwarding traffic. During communication with sink or neighbors, node i observes the rate of change in signal to noise ratio (SNR) such that sudden degradation in rate of change in signal to noise ratio could be measured. Signal to noise ratio degrades suddenly due to interference resulting from intra ban or inter ban communication. If such event occurs during communication with the sink, node i waits for some time which is less than the time out interval of upper layer and then retries. However, node i opts for another relay in case of communication with any neighboring node. The step-by-step description of the proposed protocol is stated in Algorithm 1 and frequently used terms are listed along with their meaning in Table 2.

Following data structure are needed by the algorithm.

- Boolean variable con_s which is true when there is direct connection with sink;
- Neighbor Information Table $RT_i\{SNR^j, avgRSSI^j, F^j\}$ where each entry consists of
  1. SNR^j to hold signal to noise ratio while receiving from node j at time t
  2. $avgRSSI^j$ to store average RSSI over the link between node i and neighbor j
  3. F^j to hold the fitness value of neighbor j

Complexity analysis: Algorithm 1 pursues numerous data delivery at sink s with the cost of setup packet overhead. However, single setup phase may lead to collective data transmissions hence bringing down the control message complexity to its deprecated form when evaluated with respect to the amount of data. Nevertheless, a distinct setup phase may result in one of the following scenario subject to the transmission range of a node i ready with data for the sink s and having no routing information at RT_i.

Best case: When only sink s lies in the transmission range of node i single $SETUP\_REQ^i$ from node i and single $SETUP\_RES^s$ from s are adequate to initiate data transmission. Hence, in this scenario the control message required is 2, that is complexity is constant.

```
input : :
control information of neighbors
output: :
reliable data delivery to sink
repeat
    if ((ready(data)^i OR receive(data)^j) AND !con_s) then
        broadcast(SETUP_REQ^i) ;
        if receive(SETUP_RES^s) then
            if ((SNR(t−Δt)^s − SNR(t)^s) / Δt)_i < SNR_threshold then
                update(RT_i);
                set con_s = true;
                send(data)^i to s ;
                if ((E_rem(t−Δt) − E_rem(t)) / Δt)_i < E_threshold then
                    broadcast(ID^i, ER^i(t));
                    if receive(data)^j then
                        forward(data)^j
                    end
                end
            else
                wait(t_backoff)
            end
        else
            if ((SNR(t−Δt)^j − SNR(t)^j) / Δt)_i < SNR_threshold then
                update(RT_i) ;
                calculate(F^j(t)) using Eqn7
            else
                drop(SETUP_RES^j)
            end
            set(r = j if F^j(t) = F^j(t)_max);
            forward(data)^i to r;
        end
    end
    if
    receive(broadcast)^j AND !con_s AND ((SNR(t−Δt)^j − SNR(t)^j) / Δt)_i < SNR_threshold
    then
        while exceed(buffer) do
            discard(record) for ER^j(t)_min
        end
        update(RT_i)
    else
        discard(broadcast)^j
    end
until every t time unit;
```

Algorithm 1: FindRouteToSink()

Table 2. Frequently used terms and their descriptions

Terms	Description
i, j	Any node in the network
s	Sink
$ER^j(t)$	Energy ratio of node j at time t
$E_{rem}(t)$	Remaining energy of a node at time t
E_{ini}	Initial energy of a node
$R_{(i,j)}(t)$	Reliability of the link between node i and node j at time t
$SARRatio^j(t)$	SAR ratio of the node j at time t
con_s	Connectivity to sink s
$F^j(t)$	Fitness of the node j at time t
P_{tx}	Transmission power
w_1, w_2, w_3	weights assigned to different metric
$SNR^j(t)_i$	Signal to noise ratio at node i while communicating with node j at time t
RT_i	Routing table of node i

Average and worst case: Besides, two further situations are likely to happen- (i) sink s along with other relays $j \in N$ are covered within the transmission range of i and (ii) only relay nodes are connected to node i.

In both cases, the message complexities are subject to the number of potential relays which may vary in the range $1 \leq j \leq (N-1)$ for a network of N nodes. Hence, on an average node i may receive $SETUP\_RES$ from $N/2$ neighbors with single $SETUP\_REQ^i$ and $(N-1)$ in worst case leading to control message complexity as $O(N)$ in either case.

Although the control message complexity is $O(N)$, after each setup phase, a number of data packets can be transmitted without needing the setup phase if the network topology remains stable.

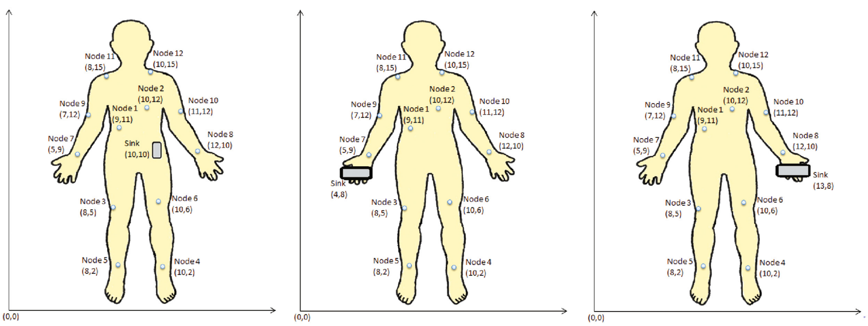
4 Simulation Results

The proposed work is evaluated through immense simulations using Castalia-3.2 [45] simulator based on OMNeT++ platform which provides support to implement distributed algorithms and/or protocols with advanced wireless channel and radio models illustrating a realistic node behavior particularly in accessing the physical layer. Highly parametric design of Castalia-3.2 enables researchers to study discrete platform characteristics relating to specific applications such as IEEE 802.15.4 functionality could be exploited to prototype intra BAN communications. Different simulation parameters used while simulating HIER are listed in Table 3 along with their default values. Any changes to it are stated precisely.

Table 3. Simulation parameters and their default values

Parameter	Default value
No. of nodes	12
No. of sink	1 (Node 0)
Time	500 s
Sending data rate	14 packets per sec (all nodes except sink)
Mobility model	Line mobility
Transmission power	−15 dBm
Sink location	Waist

12 nodes are deployed at different positions on human body as shown in Fig. 3(a) and sink is placed at waist. Simulation area of 20 m × 20 m has been exploited to provide support for relative node movements due to posture change. Experiments are carried out using ZigBee MAC protocol and Line mobility model [45]. All transmissions are made with −15 dBm transmission power. Radio parameters are regulated with values from CC2420 datasheet [45].



(a) Sink is at waist (b) Sink is at right hand (c) Sink is at left hand

Fig. 3. Node deployment strategies following different sink placements

To evaluate performance of the proposed protocol the following metrics are introduced as follows.

The ratio of total data delivered at sink ($Data^s_{rec}$) to the total data sent by each sensor i ($\Sigma_{i \in N} Data^i_{sent}$) is defined as packet delivery ratio.

$$DelRatio = \frac{Data^s_{rec}}{\Sigma_{i \in N} Data^i_{sent}} \tag{8}$$

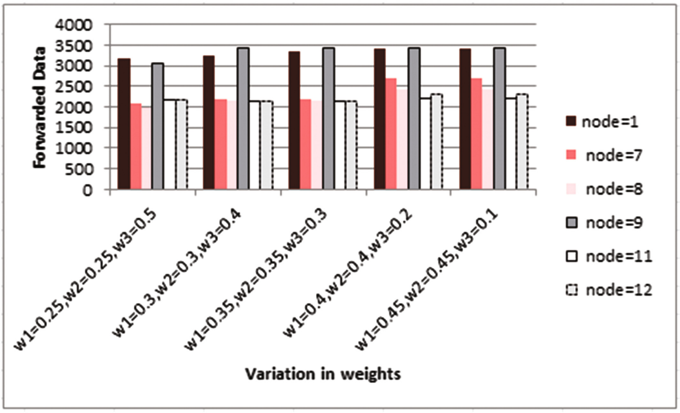


Fig. 4. Selection of weights w_1, w_2, w_3

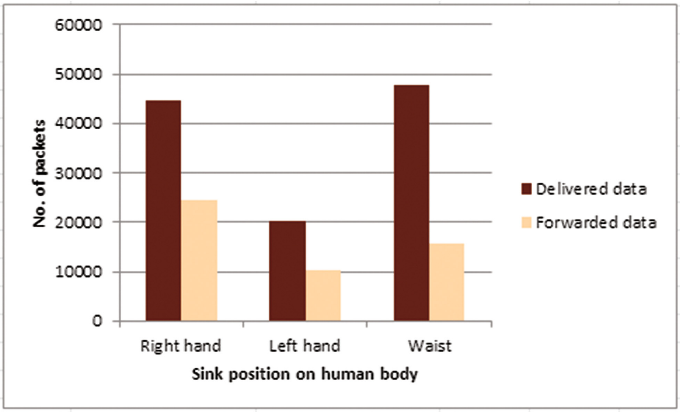


Fig. 5. Variation of forwarding traffic with corresponding delivered data at different sink positions

Likewise, forwarding ratio is measured in terms of ratio between total forwarding traffic of each sensor i ($\Sigma_{i \in N} Data^{i}_{fwd}$) to delivered data at sink s.

$$FwdRatio = \frac{\Sigma_{i \in N} Data^{i}_{fwd}}{Data^{s}_{rec}} \tag{9}$$

In the first experiment, we have observed weights(w_1, w_2, w_3) assigned to each metric for fitness calculation (that is $ER^j(t), R_{(i,j)}(t), SARRatio^j(t)$) (Eq. 7). The nodes are deployed such that few nodes are incompetent to get direct connection to sink. In such case the nodes follow the proposed routing strategy and select suitable relay to forward their data. At this point, our first focus is to assign appropriate weights such that the entire forwarding traffic is distributed among potential relays and not to overburden a single node with forwarding traffic. As we can observe from Fig. 4, due to incorporation of the metric $SARRatio^j(t)$ in fitness calculation, our goal to distribute forwarding traffic among relays is met. Herewith, we have gradually varied w_3 starting from 0.5 and accordingly adjusted two other weights w_1 and w_2 and what we found here is with w_3 as 0.2 and w_1 and w_2 as 0.4 each the forwarding traffic is not only distributed but also forwarding ratio intensifies. The scenario is even similar with w_3 as 0.1 and w_1 and w_2 as 0.45 each. Hence, we have taken w_1 and w_2 as 0.4 each and w_3 as 0.2 for our reference to carry out subsequent experiments.

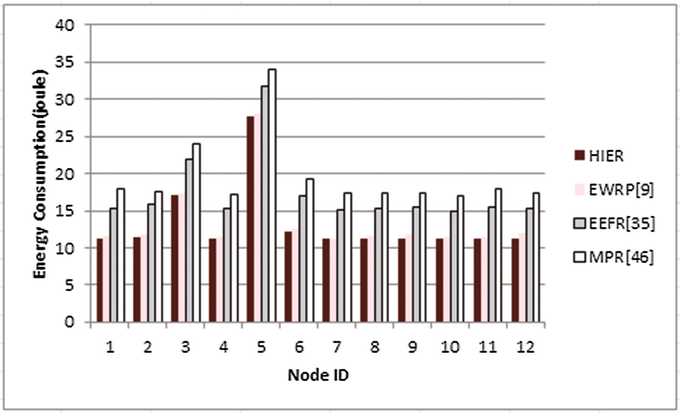


Fig. 6. Energy consumed at each node

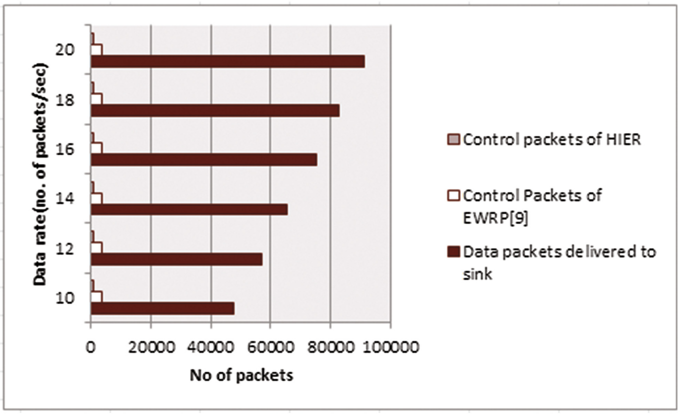


Fig. 7. Delivered data packets with corresponding control packets overhead

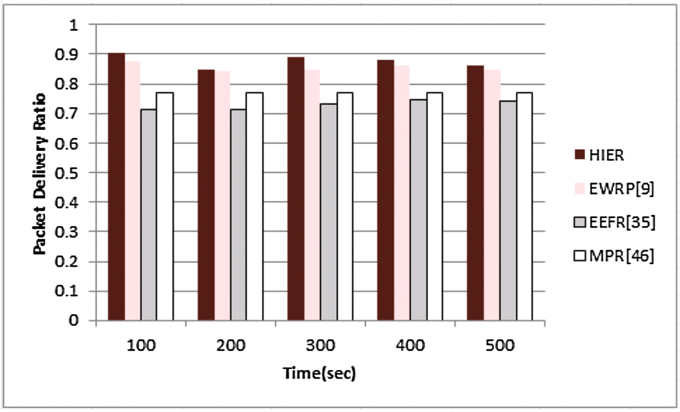
In the next experiment, we have varied the location of sink to perceive its effect on data routing. Here as presented in Fig. 3(a), (b) and (c) we have considered three major positions to place sink over human body i.e. waist, right hand and left hand. Results as obtained from Fig. 5 when sink is located at waist, most of the nodes are in a position to get direct connectivity with sink. Hence, the forwarding traffic is less with respect to the entire data delivered to sink. Accordingly, when sink is positioned on right hand, forwarding traffic grows more as few more nodes become incompetent to deliver data directly to the sink. However, according to our deployment strategy, when sink is located at left hand most of the nodes loose connectivity to sink which affects the delivery ratio as well. Hence, if sink is placed at waist it not only gets better connectivity but also becomes least affected due to posture change.

In the next experiment, we have analyzed the energy consumption of each node and compared it to the state of the art protocols. We have implemented the strategies described in [35,46] for similar simulation set up. It is observed in Fig. 6 that due to incorporation of energy efficient routing strategy, the proposed protocol requires less energy consumption as compared to the state of the art protocols. Even this protocol exhibits slightly less energy consumption than our previous work [9] as acknowledgement policy is omitted here.

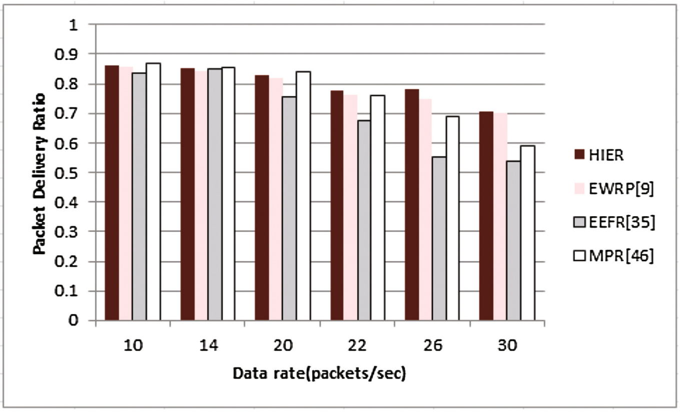
In the following experiment, we have evaluated our work in terms of overhead. Variations of delivered data packets at sink with increasing data rate are plotted with corresponding control packets. It is found in Fig. 7 that data delivery increases with rising data rate but as caching mechanism is employed in this work, more data packets could be routed with a single setup phase (i.e. control message exchange). Hence the control packets overhead remains unchanged irrespective of growing data rate and it is found to be nominal with respect to delivered data. The associated overhead is even less as compared to our previous work [9] in similar experimental setup since the acknowledgement overhead is avoided.

Next two experiments are conducted to study the behavior of the proposed protocol with time and increasing data rate respectively. The state of the art protocols are also compared with the proposed protocol HIER for similar simulation setup. As it can be seen from Fig. 8(a) HIER is able to sustain reasonable packet delivery ratio with time and outperforms existing works as well. As obtained from Fig. 8(b) channel got saturated gradually with increasing data rate, hence packet delivery ratio descends accordingly for every protocol. However, HIER exhibits better performance as compared to the existing works since this approach requires minimum control packet overhead.

In the next experiment performance of HIER is analyzed subject to increasing network size. The experiment was initiated with 5 nodes forming the network and more nodes were introduced subsequently following the deployment strategy of Fig. 3(a) to observe the behavior of packet delivery ratio in comparison to corresponding forwarding ratio. Since each node can act as relay as well, the number of forwarder increases accordingly with growing number of nodes. A



(a) Variation of packet delivery ratio with time



(b) Variation of packet delivery ratio with sending data rate

Fig. 8. Variation of packet delivery ratio with different simulation parameters

stable performance in terms of packet delivery ratio is observed with increasing network size as seen from Fig. 9 subject to increase in forwarding traffic.

Next experiment measures the delivered data in comparison to corresponding forwarding traffic with varying transmission power. This experiment shows how the proposed protocol manages data delivery with low transmission power regulating the forwarding traffic. Performance is recorded for different data rates. The results are depicted in Fig. 10. With high transmission power, nodes are capable to communicate directly to the sink and hence no forwarding traffic is required. However, with low transmission power few nodes are incompetent to transmit data directly to the sink causing more forwarding traffic in order to retain the delivery rate.

In the next experiment the performance of the proposed protocol HIER is studied subject to inter-BAN interference. When a WBAN encounters another

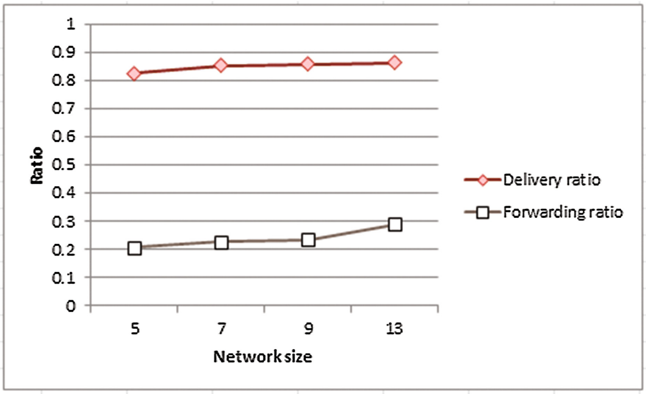


Fig. 9. Variation of packet delivery ratio with corresponding forwarding ratio with varying network size

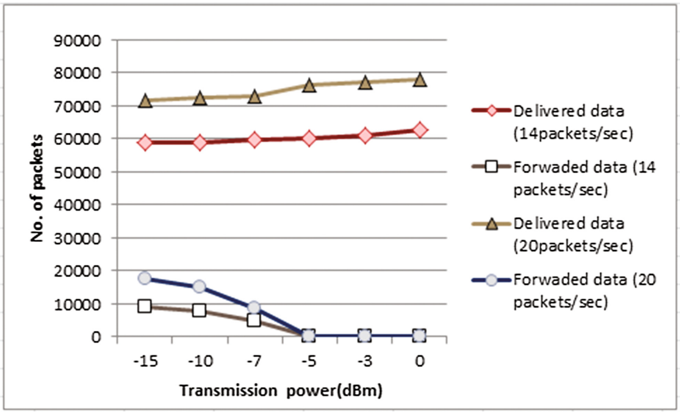


Fig. 10. Variation of delivered data with corresponding forwarding data with varying transmission power

WBAN within its communication range, inter BAN interference occurs leading to sudden degradation in SNR resulting in detrimental performance. This experiment is carried out subject to two scenarios to reflect the effect of inter BAN interference. Firstly the performance is measured when sink suffers from inter BAN interference and subsequently the behavior is noticed when a sensor node placed on right hand got affected. In the experimental setup such coexistence is introduced after 200 s and as seen from Fig. 11 performance got affected more when sink is interfered whereas packet delivery ratio could be retained well in later case by refraining the affected sensor to act as forwarder.

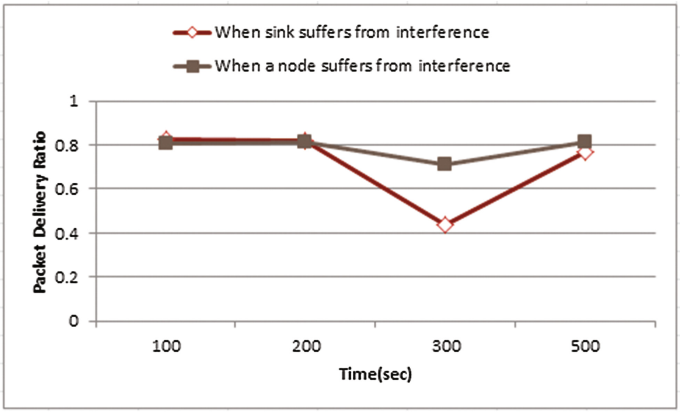
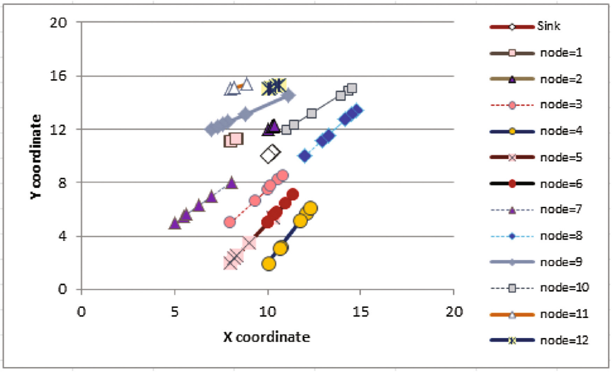
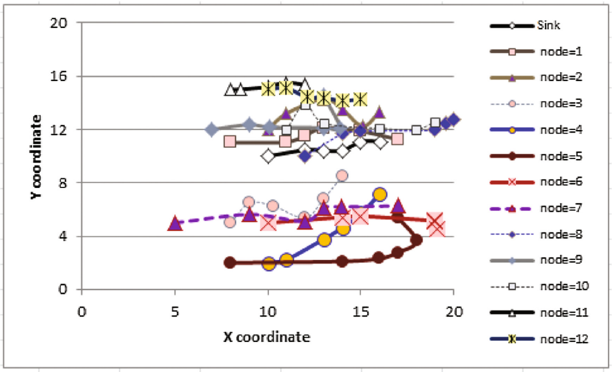


Fig. 11. Timely variation of packet delivery ratio in case of inter BAN interference



(a) Node movements according to Line mobility model



(b) Node movements according to Smooth Random mobility model

Fig. 12. Node movement with varying mobility models

A detailed analysis has been made in the next two experiments regarding relative node movements employing different mobility models. Node locations in time domain are plotted accordingly. As observed from Fig. 12(a) with line mobility model [45] movement pattern is linear and follows diagonal path starting from initial location to the corner point of the working area i.e. (20, 20) in this scenario. According to the node deployment strategy as illustrated above in Fig. 3(a) sink node placed at waist along with two other nodes (that is, node 1 and node 2) placed at chest exhibit imperceptive movements with respect to others. Besides, two more nodes (that is, node 11 and node 12) located at shoulders move unrushed as compared to the nodes deployed in hands or legs. Similar scenario has been exploited in case of smooth random mobility model [47]. Accordingly, as seen from Fig. 12(b) node movement pattern is smooth and less likely to take sharp turn. Nodes placed on hands and legs are subject to frequent posture changes than the nodes on waist or chest. This is reflected in Fig. 12(b) as well. However, the intrinsic random nature of this model influences the connectivity between nodes to a greater extent as compared to line mobility model.

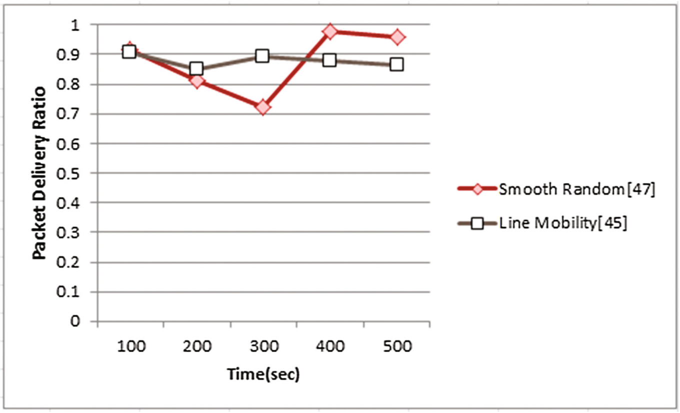


Fig. 13. Timely variation of packet delivery ratio with varying mobility model

In the subsequent experiment performance of the proposed protocol HIER is studied subject to the aforementioned mobility models. As obtained from Fig. 13, with linear movement pattern, HIER imparts steady throughput in terms of packet delivery ratio since all nodes move with comparable speed in the same direction according to the trace in Fig. 12(a). However, in case of smooth random mobility model, the different movement patterns of hands, legs with respect to waist or chest can be reflected resulting in topology change due to posture change when the transmission power of the nodes are low. Thus the packet delivery ratio obtained for Smooth Random Mobility Model is more realistic.

5 Conclusion

This paper presents a cost based energy efficient 2 hop routing protocol HIER for WBAN which addresses the inherent challenges of WBAN architecture and empowers a trade off between contradictory issues in routing decision with minimal overhead. The proposed algorithm exhibits adaptive nature in circumstances when inter BAN interference takes place. Performance of HIER is evaluated with respect to various simulation parameters for different environments such as varying sink position, varying network size etc. It is observed that, HIER outperforms the state of the art protocols for similar simulation setup in terms of energy consumed. In addition, smooth random mobility model has been implemented to trace the relative node movements in WBAN and comparative analysis has been accomplished with respect to line mobility model to elaborately investigate the effect of movement patterns on performance of routing protocols.

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