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PATIENT FACING SYSTEMS

Data-Centric Routing for Intra Wireless Body Sensor Networks

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Abstract A significant proportion of the worldwide population is of the elderly people living with chronic diseases that result in high health-care cost. To provide continuous health monitoring with minimal health-care cost, Wireless Body Sensor Networks (WBSNs) has been recently emerged as a promising technology. Depending on nature of sensory data, WBSNs might require a high level of Quality of Service (QoS) both in terms of delay and reliability during data reporting phase. In this paper, we propose a data-centric routing for intra WBSNs that adapts the routing strategy in accordance with the nature of data, temperature rise issue of the implanted bio-medical sensors due to electromagnetic wave absorption, and high and dynamic path loss caused by postural movement of human body and in-body wireless communication. We consider the network models both with and without relay nodes in our simulations. Due to the multi-facet routing strategy, the proposed data-centric routing achieves better performance in terms of delay, reliability, temperature rise, and energy consumption when compared with other state-of-the-art.

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Introduction

The population of the elderly (60+ aged) people is rapidly increasing. According to the statistics provided by Department of Economics and Social Affairs of United Nations Secretariat, it will be 15 % of the worldwide population by year 2025 [1]. Furthermore, this ratio is higher (up to 20 %) in the developed countries [2–4]. Ageing is among the key factors of chronic diseases and thus the elder people require high health-care cost [5]. To reduce the health-care cost and provide continuous and proactive health monitoring [6, 7], Wireless Body Sensor Network (WBSN) has been emerged as a promising technology where different tiny bio-medical sensor nodes (wearable, on-body, implanted) are responsible to collect the vital-sign data and send them to the local base station(s). The three tiers of WBSN's architecture are: Intra-WBSN—where the bio-medical sensor nodes route the observed data to the local base station known as Body Coordinator (BC), Inter-WBSN—where the different BCs forward the reported data towards sink(s), and Extra-WBSN—where the sink(s) forward the collected information to health-care server, physicians and/or other point of interest for monitoring and/or storage purposes [1, 3].

In addition to the inherent constraints of Wireless Sensor Networks (WSNs), WBSN has some unique challenges due to the nature and behavior of human body. The human tissues are of saline-water in nature and absorb the electromagnetic waves during transmission of the sensory data to the neighbor nodes and/or BC through wireless medium. This antenna radiation absorption and the power consumed by the implanted bio-medical sensor node for its operations may result in an increase in the temperature of the implants which may be harmful for some temperature sensitive organs such as human tissues if keep for long period of time [1–3, 8, 9]. Similarly, due to heterogeneous nature of WBSNs, different bio-medical sensor nodes generate different kind of data and impose various QoS parameters [10, 11]. Furthermore, WBSNs have high and dynamic path loss because of the electromagnetic waves absorption and postural movements of the human body due to which the traditional path loss models used in wireless communication are no more appropriate for WBSNs [12].

Different routing schemes have been proposed during last decade to address these unique challenges and constraints of WBSNs. To the best of the author's knowledge, almost all the proposed schemes aim to solve a single issue i.e., either thermal rise, or high and dynamic path loss or heterogeneous nature of generated data except TMQoS [10] and ETPA [13]. TMQoS aims to reduce temperature rise of the implanted bio-medical sensor nodes while considering the heterogeneous nature of data. On the other hand ETPA considers the path loss issue due to postural movement of human body along with thermal effects of the implanted bio-medical sensor nodes. Furthermore, most of the QoS-aware routing schemes consider inter-WBSN communication and assume that the generated data packets are received at the BC. We believe that no such integrated scheme has been proposed that considers the nature of data along with the thermal effects of implanted bio-medical sensor nodes and high path loss issue of intra-WBSNs.

The QoS-aware routing in intra-WBSN is a challenging and difficult job because of the dynamic and high path loss and the thermal effects of the implanted bio-medical sensor nodes. The heterogeneous nature of the generated data demand various QoS parameters among which delay and reliability are the most important [10, 14]. Some of the in-body bio-medical sensor nodes such as Electroencephalography (EEG), Blood Pressure, Body Temperature, and others may generate time-critical data that need to be transmitted within certain time frame. While other such as Electroencephalogram (EEG), respiratory monitoring, pH-level monitoring etc. may require to be forwarded with highest reliability [10, 11, 15].

In this paper we propose a Data-Centric Routing for intra-WBSNs that ensures the best route selection considering the required QoS parameter based on the nature of sensory data and dynamic and high path-loss of intra-WBSNs while maintaining the temperature rise of the implanted bio-medical sensor nodes at a certain acceptable level. The data-centric routing is a modular based scheme which uses separate modules for different tasks. It considers end-to-end path delay and reliability while decisions are made at each intermediate node without prior discovery and maintenance of end-to-end path. We have evaluated and compared the proposed scheme in terms of packet loss ratio due to high and dynamic path loss, packet delivery ratio, on-time packet delivery ratio, temperature rise, and energy consumption with other state-of-the-art schemes.

The rest of this paper is organized as follows: Related work is summarized in Section 2, while Section 3 describes the proposed data-centric routing for intra WBSNs. The simulation setup, results and discussion are given in Section 4. Finally, Section 5 concludes this paper.

Related work

Different routing protocols have been proposed for WBSNs during last decade. In most cases the authors have tried to address a single issue i.e., either to reduce the thermal effects of the implanted bio-medical sensor nodes, or to solve the high and dynamic path loss issue, or to provide the required QoS based on the nature of generated data packets. Thermal Aware Routing Algorithm (TARA) [8] is the first routing scheme for intra-WBSNs that aims to maintain the temperature rise of the implanted bio-medical sensor nodes at certain level. Neighbor nodes observe each other's activities to estimate their temperatures. If the temperature rise of any neighbor node is beyond a certain level, that node is considered as hotspot node. TARA uses withdrawal mechanism to route the data packets through non-hotspot nodes where any node having hotspot node in its neighborhood returns the data packets to sender to forward them towards the destination using alternative routes. Due to this withdrawal mechanism, TARA experiences low reliability, high delay and more energy consumption.

Least Temperature Routing (LTR) 16] is another temperature-aware routing mechanism that selects the next-hop node based on its temperature rise and to avoid routing loops, it keeps a record of the visited nodes. It uses greedy approach, due to which the packets are not directed towards destination and thus increases the hop-counts. This results in high delay and low reliability. An improved version of LTR is Adaptive Least Temperature Routing (ALTR) [16], where shortest hop scheme is adapted in case the hop-counts exceeds a pre-defined limit. The shortcomings of LTR and ALTR are addressed by Least Total Route Temperature (LTRT) [9] where the route from source to destination having least temperature is selected among all possible routes using Dijkstra's algorithms. All the temperature-aware routing protocols select the next-hop node based on the temperature rise of the individual nodes or entire route. They do not consider the required QoS parameters based on the nature of sensory data and the dynamic and high path loss issue which makes them unrealistic solutions for intra-WBSNs.

The high and dynamic path loss issue of intra-WBSNs has gained the attention of the researcher during last decade and different schemes have been proposed. The routing schemes proposed in [17–19] use store and forward/flood approaches to forward the received/generated data packets towards the destination node. While the Opportunistic routing [20], uses Line-of-Sight (LoS) and None-Line-of-Sight (NLoS) approach to send the data packets. The neighbor nodes only communicate with each other when they are in LoS otherwise a relay node is informed to initiate communication between them. All these routing schemes are based on periodically updated cost functions. When a packet is generated or received at any node, it looks for neighbor node with minimum cost function to forward the generated or received data packets. If no such neighbor node is available, it stores the data packets, which results in high delay. Furthermore, they ignore the heterogeneous nature of generated data as well the thermal effects of the implanted biomedical sensor nodes.

In [12, 21–23] the authors have used special kind of nodes known as *relay nodes* to address the high and dynamic path loss issue. The relay nodes can be either well-placed on the human body or equipped within clothing (wearable) and thus minimize the small surgical operations which are performed to replace the in-body biomedical sensor nodes. Furthermore, the relay nodes are helpful in order to enhance the reliability, reduce the energy consumption and thermal effects of the implanted bio-medical sensor nodes. Transmission consumes more energy as compared to other operations of the sensor nodes which can be reduced with the help of these relay nodes. Moreover, the antenna radiation absorption during wireless communication is one of the two reasons that cause the temperature rise of the bio-medical sensor nodes which can be reduced by using the on-body relay nodes.

The heterogeneous natured Intra-WBSNs generate different kinds of data, which is categorized into Critical Data (CD), Delay Sensitive Data (DSD), Reliability Sensitive Data (RSD) and Normal Data (ND) in [10, 11, 15, 24, 25]. A certain time deadline must be ensured for DSD packets and some packet losses is acceptable while RSD packets need to be transmitted with highest reliability and can tolerate some delay. On the other hand, CD packets strictly require least delay and highest reliability while ND packets do not impose any such constraints. All the existing QoS-aware routing schemes consider inter-WBSN communication except TMQoS [10] which is designed for Intra-WBSNs. LOCALMOR [15] and DMQoS [11] classify the generated data into CD, DSD, RSD, and ND. LOCALMOR uses two sinks (primary and secondary) for each patient and the data packets are blindly forwarded towards both sinks which is being addressed in DMQoS. QPRD [24] categorizes the data into DSD and ND while QPRR [25] into RSD and ND and both are designed to display the vital-signs of the patient on a medical display inside hospital. All these QoS-aware routing schemes designed for inter-WBSN do not consider the thermal effects of the implanted bio-medical sensor nodes and the high and dynamic path loss issue of intra-WBSNs.

To the best of our knowledge, TMQoS is the only QoS-aware that aims to provide the required QoS and maintains the thermal effects of the in-body bio-medical sensor nodes to certain acceptable level. It results in better performance as compared to other state-of-the-art schemes [8, 9] but it does not take into account the high and dynamic path loss issue of intra-WBSNs which makes it and its performance unrealistic. Furthermore, it only consider the QoS metrics of those neighbor nodes that have least number of hop counts for all categories of data packets. However, RSD and ND packets do not impose in such delay constraints and can tolerate some delay.

As discussed above, all the proposed schemes addressed only a single issue except TMQoS and ETPA, where the temperature rise is considered along with QoS parameters and high path loss issue respectively. In our early proposed schemes [26, 27], we have addressed QoS-aware routing for RSD and critical data respectively. In this paper we propose data-centric routing for intra-WBSNs that incorporates the thermal effects of implanted bio-medical sensor nodes and high path loss issue of intra-WBSNs along with other QoS concerns for DSD, RSD and ND. The proposed routing scheme selects next-hop node based on end-to-end path delay for DSD, end-to-end path reliability for RSD and end-to-end temperature rise for ND packets. Doing so, not only ensures the desired QoS demands based on nature of data but also helps in controlling the thermal effects of implanted bio-medical sensor nodes.

Proposed scheme

Network model

We have used two types of networks models in this paper: data-centric routing with and without relay nodes, which are discussed in detail in the following.

Data-centric routing without relay nodes

In Data-Centric Routing without relay nodes (DCR), different in-body bio-medical sensor nodes and the on-body BC can be modeled using connectivity graph as given below.

$$G = (V, E) \tag{1}$$

Where V represents the union of S—the set of N implanted bio-medical system and BC i.e.,

$$V = \{S\} U \{BC\} \tag{2}$$

$$S = \{s_1, s_2, s_3, \dots\dots\dots s_n\} \tag{3}$$

E represents the set of m possible wireless communication links between a bio-medical sensor node and BC, and/or between any two bio-medical sensor nodes i.e.,

$$E = \{e_1, e_2, e_3, \dots\dots\dots e_m\} \tag{4}$$

It is assumed that the bio-medical sensor nodes are implanted inside human body, energy constrained (battery powered), fixed, use limited transmission power, and can act as source and/or forwarding nodes. The BC has no energy constraint (replaceable power source).

Data-centric routing with relay nodes

In Data-Centric Routing with Relay nodes (DCRR), special type of nodes known as *relay nodes* same as in [12, 21–23] are being used which are responsible to forward the sensory data of the bio-medical sensor nodes towards the BC. Equation (1) can be used to model the DCRR network model, where V represents the union of S—set of all n bio-medical sensor nodes same as in Eq. (3), R—set of n relay nodes and BC.

$$V = \{S\} U \{R\} U \{BC\} \tag{5}$$

$$R = \{r_1, r_2, r_3, \dots\dots\dots r_n\} \tag{6}$$

E represents the set of m possible wireless communication links between any two relay nodes, between a bio-medical sensor node and a relay node, and/or between a relay node and BC, same as in Eq. (4). The assumptions made for DCRR are same as that of DCR except that bio-medical sensor nodes are used only as source nodes while relay nodes are responsible to forward the sensory data, and the bio-medical sensor nodes use lower transmission power as compared to the relay nodes.

Classification of sensory data

The designed aim of the proposed scheme is to provide the required QoS parameter based on the nature of the sensory data. In WBSNs the QoS requirements for various applications are total different from one another. The sensory data of some bio-medical sensor nodes needs to be delivered in real time while others require to be transmitted with highest reliability. Thus considering delay and reliability as QoS metrics, the sensory is being classified into following three types.

- Type 1 DSD packets need to the transmitted within certain time deadline and some packet losses are acceptable.
- Type 2 RSD packets require highest possible reliability but can tolerate some delay.
- Type 3 ND packets do not impose any such constraint of delay and/or reliability.

Proposed data-centric routing for intra wireless body sensor networks

As shown in Fig. (1), the proposed data-centric routing is a cross-layered approach uses different modules for various tasks. The data and/or Hello packets from the neighbor nodes and/or BC are received at *MAC receiver* while the task of the *packets classifier* is to separate them as data and Hello packets. The data packets are forwarded towards data packets classifier while the Hello packets to routing module. Similarly, the *MAC transmitter* is responsible to send the received and/or generated data and Hello packets to the neighbor nodes and/or BC. Once the data packets are received either from the neighbor nodes or from the upper layers, it's the job of the *data packets classifier* to categorize them as DSD, RSD and ND packets and send them to delay-aware, reliability-aware and temperature-aware modules respectively. The following subsections discuss the other modules of the proposed scheme.

Delay-aware module

The task of delay-aware module is to select best possible route to send *DSD* packets. At any node n_i, when a DSD packet P is received, the Delay-Aware Algorithm, given below in Algorithm (1), looks at the routing table RT and selects those neighbor nodes belongs to routing table whose link quality $LQ_{i,j}$ between nodes n_i, and n_j, is higher or equal to the required link quality LQ_{req} and store them in NN_{LQ} (lines: 1–4). The packet is P is dropped in case of no such node (lines: 5–6). In case of non-empty NN_{LQ}, it chooses only those neighbors nodes belongs to NN_{LQ}, whose end-to-end path delay $PD_{i,j}$, from node n_i to BC through node n_j, is less than or equal to the required delay D_{req} and store them into NN_D (lines: 7–10). In case of null NN_D, the packet P is dropped (lines: 11–12), in case single entry in NN_D, that single neighbor node is selected as desired next hop DNH (lines: 13–15). On the other hand, in case of more than one entry in NN_D, temperature-aware module is called with packet P and NN_D as inputs (lines: 16–17).

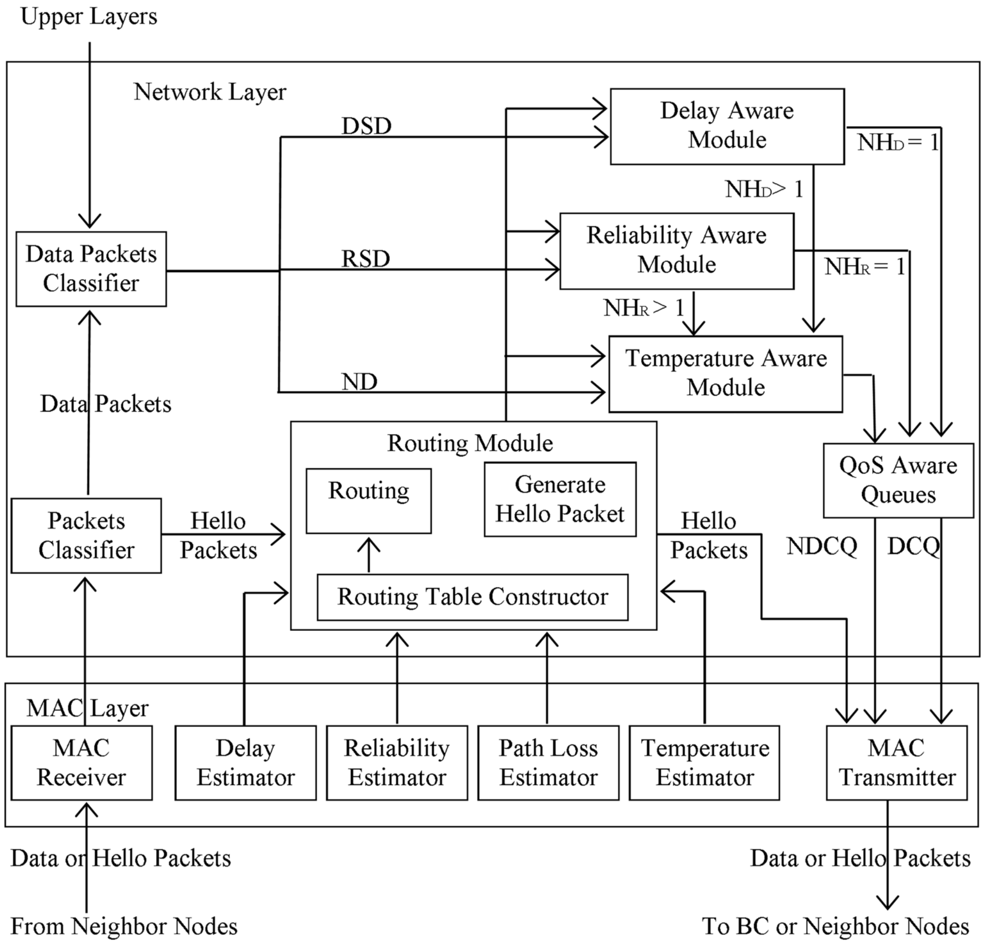


Fig. 1 Block Diagram of Data Centric Routing Scheme

Reliability-aware module

The reliability-aware module of the proposed DCR is responsible to select best possible route for the *RSD* packets. Once a data packet *P* is received at reliability aware module, the Reliability Aware Algorithm given in Algorithm (2), searches the routing table *RT* and the desired next hop *DNH* node is selected in the same manner as in delay-aware module except that the decision is made based on the end-to-end path reliability $PR_{i,j}$, from node n_i to *BC* through node n_j (lines: 1–17).

Algorithm 1: Delay Aware Algorithm

```
Inputs: DSD Packets, and RT
for each packet 'P' ∈ DSD do
    for each node n_i ∈ RT do
        if LQ_i,j > = LQ_req then
            put node n_i into NN_LQ
    if NN_LQ = = NULL then
        drop the packet
    else
        for each node n_i ∈ NN_LQ do
            if PD_i,j > = D_req then
                put node n_i into NN_D
    if NN_D == NULL then
        drop the packet
    else if NN_D = = 1 then
        DNH = k ∈ NH_D
        send packet to DNH
    else
        call Temperature Aware Module with inputs P, and NH_D
```

Temperature-aware module

The temperature-aware module is being used by all types of generated and/or received data packets. For any packet *P* received at temperature aware module that belongs to *ND* packets, the temperature aware algorithm given in Algorithm (3), looks at the routing table *RT* and selects the desired next hop *DNH* using the same procedure as in delay and reliability aware algorithms except that decision is made based on the end-to-end path's temperature rise *PTR* (lines: 2–12). On the hand, for any packet *P* received that belongs to *DSD* or *RSD* packets, the node n_j belongs NN_D or NN_R is being selected as desired nest hop *DNH* which has minimum end-to-end path's temperature rise *PTR* (lines: 13–17).

Routing module

Routing table constructor, routing table and Hello packets constructor are the three sub-modules of routing module. The routing table constructor uses the information provided by different parameter estimators and by neighbor nodes through Hello packets to build and/or periodically update routing table. The end-to-end path delay, end-to-end path reliability and end-to-end path temperature can be calculated using Eqs. (7), (8) and (9) respectively.

$$PD_{i,j} = PD_{i,j} + ND_{ni} \tag{7}$$

$$PR_{i,j} = PR_{i,j} \times LR_{i,j} \tag{8}$$

$$PT_{i,j} = PT_{i,j} + NT_{ni} \tag{9}$$

After building and/or periodically updating the routing table, each node informs its neighbor nodes through Hello packets generated by Hello packets constructor using the information provided by routing table. Figure (2-a) shows the different parameters of the routing table while Fig. (2-b) illustrates other than the usual parameters of the Hello packets. The different parameters used in Fig. (2) are explained in Table (1).

Algorithm 2: Reliability Aware Algorithm

```
Inputs: RSD Packets, and RT
1.  for each packet 'P' ∈ RSD do
2.    for each node n_i ∈ RT do
3.      if LQ_i,j > = LQ_req then
4.        put node n_i into NN_LQ
5.    if NN_LQ = = NULL then
6.      drop the packet
7.    else
8.      for each node n_i ∈ NN_LQ do
9.        if PR_i,j > =  R_req then
10.         put node n_i into NN_R
11.   if NN_R == NULL then
12.     drop the packet
13.   else if NN_R = = 1  then
14.     DNH = k ∈ NH_R
15.     send packet to DNH
16.   else
17.     call Temperature Aware Module with inputs P, and NH_R
```

Delay estimator

The task of the delay estimator is to measure the delay occur due to processing, queuing, transmission and propagation at any node n_i. Queuing and transmission are the dominant factors that cause total delay. Processing delay is the time required to process the packets which is insignificant and is considered to be same for all types of data packets. While propagation is the speed of light and thus both processing delay and propagation delay can be ignored.

DCR considers the queuing delay only for DSD packets and is the time interval required for a packet to be in queue for transmission. Exponentially Weighted Moving Average (EWMA) formula [28], given in Eq. (10) is being used to calculate the queue delay. Where QD_{ni} is the queue delay at node n_i and α is smoothing factor constant having value between 0 and 1. In our simulation, we have use α=0.2, same as in [10, 11, 24]. The initial value of QD_{ni} is the time for which the first DSD packet remains in the queue.

$$QD_{ni} = \alpha QD_{ni} + (1-\alpha) QD_{ni} \tag{10}$$

The transmission delay $TD_{i,j}$ of the link $L_{i,j}$ between nodes n_i and n_j, is the time interval between the time when a packets enters the MAC layer to the time when it is either successfully transmitted or dropped. The Transmission Delay $TD_{i,j}$ can be calculated using formula [24] given in Eq. (11), where DR_{bits} is the data rate, SP_{bits} is the size of each packet, NP is the number of packets transmitted in time window of δt. At any node n_i, the node delay ND_{ni} is given by Eq. (12).

$$TD_{i,j} = \left(\frac{1}{DR_{bits}}\right) \times \left(\frac{\sum_{z=1}^{NP} SP_{bits}(z)}{NP}\right) \tag{11}$$

$$ND_{ni} = QD_{ni} + TD_{i,j} \tag{12}$$

Reliability estimator

The reliability of the link between any two neighbor nodes can be calculated by reliability estimator.

Fig. 2 Structure of (**a**) Routing Table and (**b**) Hello Packet

ID_{Dest}	Loc_{Dest}	ID_{nj}	$LQ_{i,j}$	$PR_{i,j}$	$PD_{i,j}$	$PT_{i,j}$	Loc_{nj}

(a)

ID_{Dest}	Loc_{Dest}	ID_{nj}	$LQ_{i,j}$	$PR_{i,j}$	$PD_{i,j}$	$PT_{i,j}$	D_{nj}	$LR_{i,j}$

(b)

Window Mean with Exponentially Weighted Moving Average (WMEWMA) formula [29] which is more appropriate approach for wireless sensor networks, given in Eq. (13) is being used to measure the link reliability $LR_{i,j}$, of the link $L_{i,j}$, between two neighbor nodes n_i and n_j.

$$LR_{i,j} = LR_{i,j} \times \beta + (1-\beta) \times P_{average} \tag{13}$$

β is the average weighting factor having value between 0 and 1 and in our simulation we use 0.4, same as in [10, 11, 25]. Similarly $P_{average}$ is the probability of successful transmission over a time window of δt, given in Eq. (14), where N_{ack} is the number of acknowledged packets and N_{trans} is the number of transmitted packets.

$$P_{average} = \frac{N_{ack}}{N_{trans}} \tag{14}$$

Temperature estimator

The temperature of the implanted bio-medical sensor nodes can be raised as a result of antenna radiation absorption by human tissues and power consumption due to nodes' operations. Specific Absorption Rate (SAR) is the rate at which the human tissues absorb the radiation energy per unit weight and is given in [8] as:

$$SAR = \frac{\sigma|E|^2}{\rho} \tag{15}$$

Where ρ is the density of human tissue, σ is the electric conductivity of human tissue, and E is induced electric field generated by radiation. On the other hand, the power consumption due to nodes' operations can be calculated as the density of power consumption P_c, i.e., power consumed divided by volume of the bio-medical sensor node. Pennes Bioheat equation [30], given in Eq. (16) can be used to calculate the temperature rise. The different parameter used in Eq. (16) are given in Table (2) while their values are taken from [31].

$$\frac{dT}{dt} = \frac{K\nabla^2 T - b(T-T_b) + \rho SAR + P_c}{\rho C_p} \tag{16}$$

Path loss estimator

The traditional path loss models of wireless communication are no more appropriate for Intra-WBSNs because of the high and dynamic path loss due to electromagnetic waves absorption and postural movement of the human body. The mean path loss $PL_{i,j}$ can be defined as function of the distance $d_{i,j}$ between the neighbor nodes n_i and n_j, and is calculated (in decibel) by semi-empirical formula given in [12], which is

Table 1 Description of the parameters used in Fig. (2)

Parameter	Description
ID_{Dest}	Destination (body coordinator) ID
Loc_{Dest}	Coordinates of the body coordinator
ID_{nj}	ID of the neighbor node n_j
$LQ_{i,j}$	Link Quality between nodes n_i, and n_j
$PD_{i,j}$	End-to-end path delay from node n_i to BC through node n_j
$PR_{i,j}$	End-to-end path reliability from node n_i to BC through node n_j
$PT_{i,j}$	End-to-end path temperature from node n_i to BC through node n_j
Loc_{nj}	Coordinates of the neighbor node n_j
$LR_{i,j}$	Link reliability between nodes n_i and n_j
D_{ni}	Delay at node n_j

Table 2 Description of the parameters used in Eq. (16)

Parameter	Description
dT/dt	Rate of temperature rise
$K\nabla^2 T$	Heat caused by tissue's thermal conductivity
$b(T-T_b)$	Temperature rise due to blood perfusion
ρSAR	Heat generated due antenna radiation absorption
P_c	Heat caused by power consumption due to nodes' operation
ρ	Mass density
C_p	Tissue's specific heat

based on the Friis formula [32] as in Eq. (17), where PL_0 is the path loss at the reference distance d_0. But in reality, the path loss model for intra-WBSNs is dynamic in nature and by considering the zero-mean Gaussian random variable X_σ with standard deviation σ, Eq. (17) can be formulated as given in Eq. (18).

$$PL_{i,j} = PL_0 + 10n\log\frac{d_{i,j}}{d_0} \quad (17)$$

$$PL_{i,j} = PL_0 + 10n\log\frac{d_{i,j}}{d_0} - X_\sigma \quad (18)$$

The link quality $LQ_{i,j}$ can be formulated by using Eq. (19) same as in [12], where P_{trans} is the transmitting power, $PL_{i,j}$ is the path loss given in Eq. (18) and LQ_{thre} is the threshold level.

$$LQ_{i,j} = \frac{1}{2} - \frac{1}{2} erf\left(\frac{-P_{Trans} + PL_{i,j} + LQ_{thre}}{\sqrt{2\pi\sigma}}\right) \quad (19)$$

The two neighbor nodes n_i and n_j, can communicate with each other only if the link quality $LQ_{i,j}$ is equal to or greater than a certain threshold level LQ_{thre}. For more reliable communication, 99 % of the link quality can be required [12]. We use the whole body path loss model proposed in [12] Furthermore, it has also been shown in [12] that the path loss model of entire human body is in accordance with different parts of the human body.

QoS-aware queues

Once the desired next hop based on the nature of the sensory data has been selected, the data packets are directed towards the QoS-aware queues, where two separate queues are maintained in order to provide the demanded QoS. The data packets that need to be forwarded within certain time limit (DSD) are queued in Delay Constraint Queue (DCQ) while the data packets that can tolerate some delay (RSD and ND) are queued in Non-Delay Constraint Queue (NDCQ). DCQ has higher priority as compared to NDCQ. To avoid the indefinitely blocking of the data packets waiting in NDCQ, we use the same procedure as described in [10, 11], where the data packets from NDCQ are moved to DCQ after waiting for a certain period of time.

Simulation results and discussion

Simulation setup

NS2 (Network Simulator Version-2) has been used to simulate and evaluate the performance of our proposed Data-Centric Routing algorithm. NS2 is a discrete event simulator and supports multi-hop routing for wired and wireless networks with complete MAC, Data Link and Physical layer models. Two network models with and without relay nodes: DCR and DCRR have been used to evaluate the performance of the proposed algorithm against other state-of-the-art schemes. Human body is the deployment area and different number of sensor nodes (10, 15, 20, 25 and 30) is used during simulation. Some of the implants generate constrained data packets (either DSD or RSD packets) while others generate normal data packets. Average results have been taken by changing the sensor nodes generating constrained and normal data packets in such a way that every sensor node generates DSD, RSD and ND packets. We have compared our proposed scheme with LTRT [9] and TMQoS [10] and evaluated its performance in terms of packet loss ratio due to path loss, average packet delivery ratio, average on-time packet delivery ratio, average energy consumption and average temperature rise. The simulation results reveal that our proposed Data-Centric Routing successfully achieves its design objectives. The configuration of the network parameters used in simulation, are given in Table 3.

Table 3 Network parameters

Deployment	Area	3 m x 2 m
	Number of Nodes (DCR)	10–30 Biomedical Sensor Nodes 01 Body Coordinator
	Number of Nodes (DCRR)	10–30 Biomedical Sensor Nodes 01 Body Coordinator 10–30 Relay Nodes
	Initial Energy	50 Joule
	Buffer Size	60 Packets
	Transmission Range (DCR)	40 cm
	Transmission Range (DCRR)	40 cm (Relay Nodes) 20 cm (Sensor Nodes)
	Transmission Power (DCR)	$8.5872e^{-4}$
	Transmission Power (DCRR)	$8.5872e^{-4}$ (Relay Nodes) $1.0872e^{-4}$ (Sensor Nodes)
	Bit Error Rate	10^{-2}–10^{-4}
Tasks	Application Type	Event Driven
	Propagation Model	TwoRayGround
	Network Interface Type	WirelessPhy
	Traffic Type	Constant Bit Rate (CBR)
MAC	IEEE 802.15.4	Default Values
Simulation	Time	1000 s

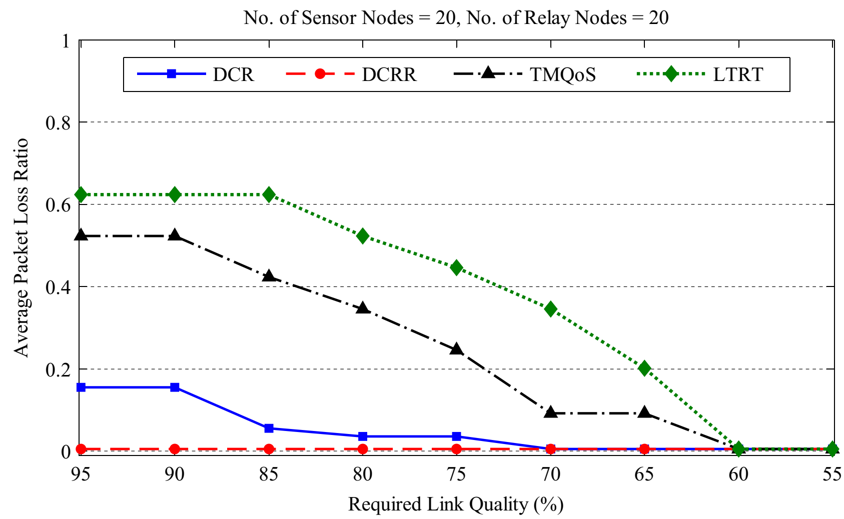


Fig. 3 Average packet loss ratio vs required link quality at different data generation rates

Results and discussion

Impact of link quality

Figure 3, illustrates the average packet loss ratio Vs required link quality at different data rates. It is clear the DCRR out-performs the other state-of-the-art schemes while DCR results in slightly poor performance at high required link qualities but much better as compared to TMQoS and LTRT. The reason behind the poor performance of TMQoS and LTRT is that they don't consider the high and dynamic path loss of the implanted biomedical sensor nodes. Furthermore, as compared to LTRT, TMQoS results in low packet loss ratio because it considers the nature of the sensory data which is compared ignored in LTRT.

Impact of TTL deadlines

Figure 4 (a) and (b) show the average on-time packet delivery ratio with respect to different TTLs considering different link qualities for DSD packets at low and high data rates respectively. It is clear that even at very tight time constraint DCR shows very good performance as compared to others. At slightly relaxed time constraint, DCRR out-performs the others at low data rates, while at high data rates DCRR performance is slightly poor as compared to DCR and it might be because of the high congestion at relay nodes. DCRR shows poor results at tight time constraint due to the delay caused by relay nodes. On the other hand, both at low and high data rates TMQoS and LTRT performance is becoming better with relaxed time constraint but still very poor as compared to DCR and DCRR due to not considering the path loss issue of implanted bio-medical sensor nodes. As compared LTRT, TMQoS results in better performance because TMQoS considers the nature of the sensory data along with the thermal effects of the implants while the LTRT only considers the temperature rise issue.

Impact of required reliability

Figure 5 (a) and (b) show the average packet delivery ratio of RSD packets with respect to required reliability at low and high data rates respectively. Both Fig. 5 (a)

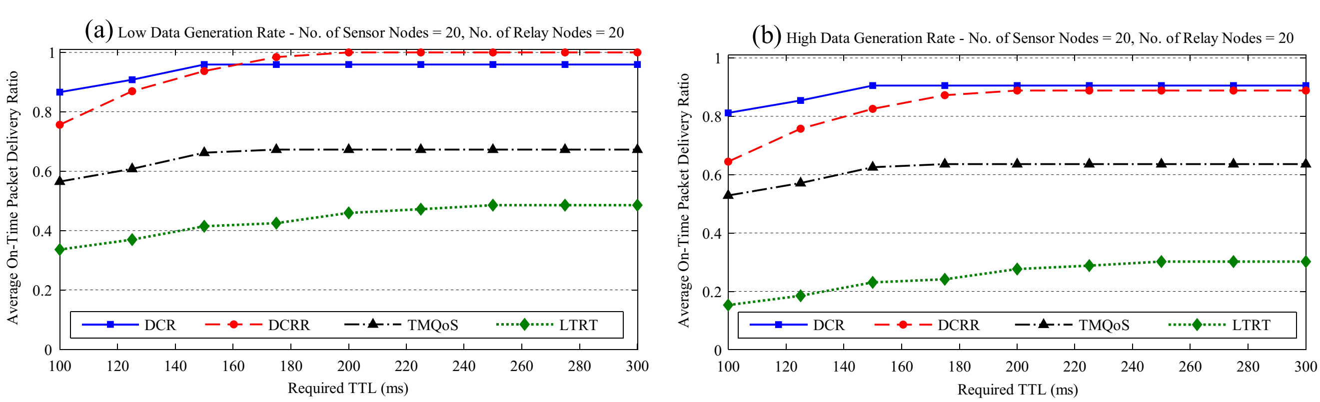


Fig. 4 Average on-time packet delivery ratio for DSD packets vs required TTL at different link qualities (**a**) low data generation rate (**b**) high data generation rate

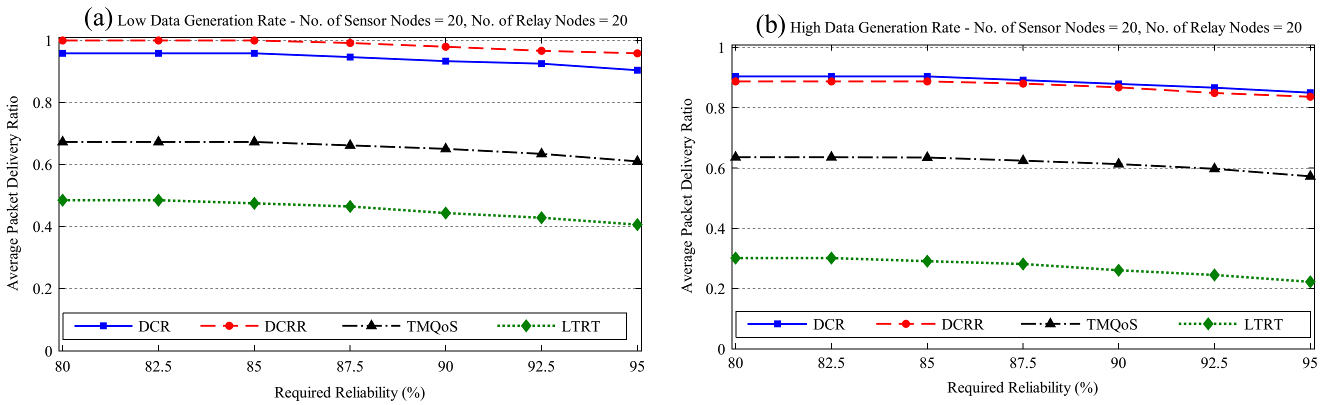


Fig. 5 Average packet delivery ratio vs required reliabilities at different link qualities (**a**) low data generation rate (**b**) high data generation rate

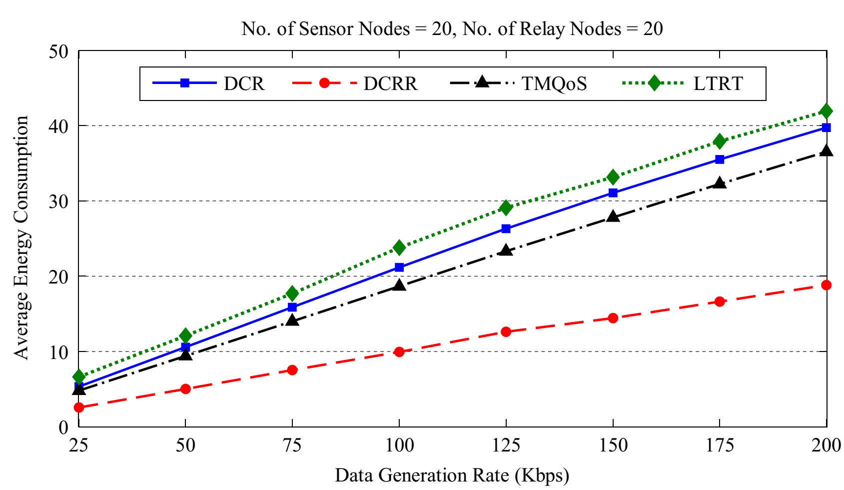
and (b) reveal that DCRR has better performance among all at low data rates while at high data rates it is replaced by DCR due to high congestion at relay nodes. In all cases TMQoS out-performs the LTRT at all data rates and required reliabilities. The reasons behind the poor performance of TMQoS and LTRT are the same i.e., TMQoS considers the thermal effects of the implants along with the required QoS parameter but completely ignore the high and dynamic path loss issue of intra-WBSNs. Secondly, it selects the desired next-hop node based on hop count even the RSD packets can tolerate some delay. On the other hand, LTRT aims to reduce the temperature rise but ignore the heterogeneous nature of the generated data and the path loss issue of the implanted bio-medical sensor nodes.

Impact of data generation rate

Figures 6 and 7 show the average energy consumption and average temperature rise of the implanted bio-medical sensor nodes considering different link qualities with respect to different data generation rates respectively. Both figures show that the energy consumption and the temperature rise are increasing with high data rates. High data rate means more communication and more communication results in more energy consumption and high temperature rise. In both cases DCRR results in better performance as compared to others because the sensor nodes are used only to sense the vital-signs data of the human body while the relay nodes are responsible for forwarding the generated data packet. As TMQoS selects the desired next-hop node based on hop counts while in case of DCR it is selected based on the link quality, due to which TMQoS consumes slightly less energy as compared to DCR. In case of temperature rise LTRT out-performs the TMQoS and DCR because its main concern is to reduce the thermal effects of the implanted bio-medical sensor nodes.

Figure 8, illustrates the average packet delivery ratio at different link qualities with respect to data generation rates. Figure 8 shows that the packet delivery ratio is decreasing with increase in data generate rate for all schemes. At low

Fig. 6 Average energy consumption vs data generation rates at different link qualities



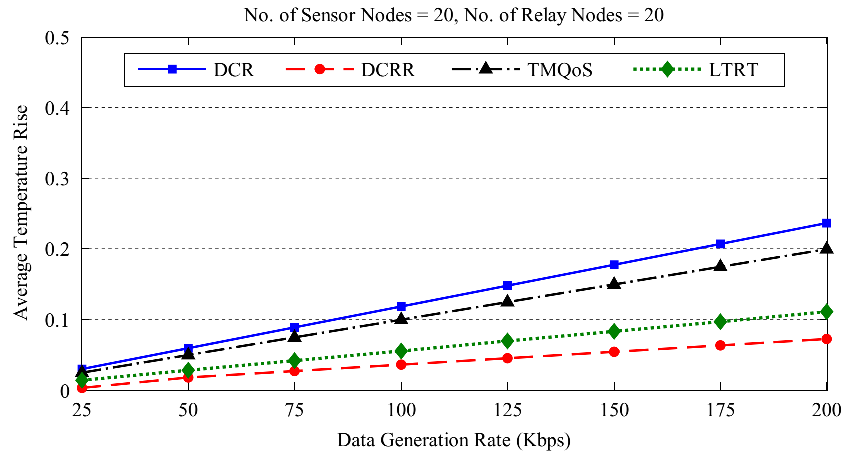


Fig. 7 Average temperature rise vs data generation rates at different link qualities

and medium data rates DCRR out-performs the others but at high data rates its performance is slightly poor as compared DCR and it might be due to high congestion at the relay nodes. The reasons behind the poor performance of TMQoS and LTRT are same.

Impact of network size

Figure 9 shows the impact of network size over the average packet delivery ratio at different link qualities and data generation rates. It is clear from the figure that at high network size of the performance of all schemes is slightly deceasing which might be due to high congestion of the sensor and/or relay nodes near BC. Similarly, at low and medium network size DCRR outperforms the others while at high network size DCR replaces DCRR which might be due to high network congestion on the relay nodes. Moreover, the performance of both DCR and DCRR is significantly better compared to TMQoS and LTRT while LTRT results in poor performance compared to TMQoS at all network sizes. TMQoS consider the required QoS parameters along with thermal effects of the implants while LTRT aims to reduce the temperature of the in-body sensor nodes. Both TMQoS and LTRT overlook the high and dynamic on and in-body path loss, which is considered along with the required QoS parameters and thermal effects of the implanted bio-medical sensor nodes in both DCR and DCRR.

Conclusion

In this paper we have proposed data-centric routing for intra WBSNs that adapts the routing strategy in accordance with the nature of data, thermal effects of the implanted bio-medical sensors, and dynamic path loss caused by postural movement of human body. Based on nature of sensory data, it is classified as delay-sensitive, reliability-sensitive and normal data. Besides the required QoS parameter, it also consider the high and dynamic path loss of the Intra-WBSNs due to postural movements of the human body and the thermal effects of the implanted bio-medical sensor nodes due the antenna radiation absorption which may be harmful for some

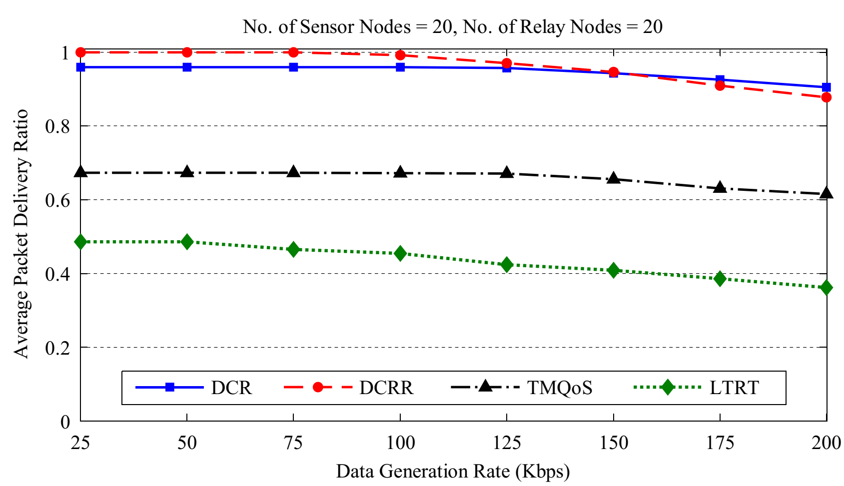


Fig. 8 Average packet delivery ratio vs different data generation rates at different link qualities

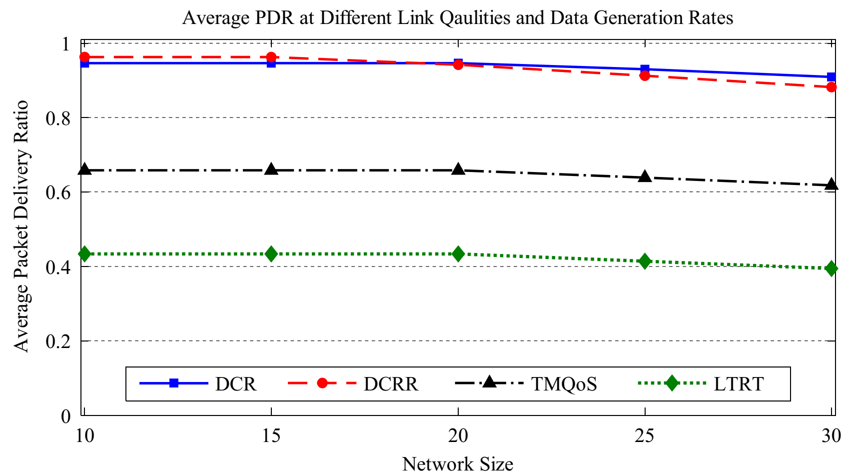


Fig. 9 Average packet delivery ratio vs network size at different link qualities and data generation rates

temperature sensitive organs such as tissues if kept for long period of time. Two network models with and without relay nodes: DCR and DCRR have been used. The proposed routing scheme considers end-to-end path delay and/or reliability from the source bio-medical sensor node to the destination node (BC) while the decisions are made locally without maintaining end-to-end path. Simulation results revealed improved performance of the proposed data-centric routing as compared to other state-of-the-art schemes. As future work, we plan to consider routing the critical data which requires on-time data delivery with highest reliability.

Conflict of interest The authors declare no conflict of interest.

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