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Optimized cost effective and energy efficient routing protocol for wireless body area networks

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ABSTRACT

The increase in average lifespan and huge costs for health treatments have resulted in cost effective solutions for healthcare management. Wireless Body Area Network (WBAN) is a promising technology for delivering quality healthcare to its users. Low power devices attached to the body have limited battery life. It is desirable to have energy efficient routing protocols that maintain the required reliability value for sending the data from a given node to the sink. The current work proposes two protocols: Optimized Cost Effective and Energy Efficient Routing protocol (OCER) and Extended-OCER (E-OCER). In OCER, optimization using Genetic Algorithm (GA) is applied to the multi-objective cost function with residual energy, link reliability and path loss as its parameters for selecting the most optimal route from a given body coordinator to the sink. Distance between any two sensor nodes is reduced by applying multi-hop approach. E-OCER extends the work of OCER by considering inter-BAN communication. Performance of OCER is compared with other existing energy aware routing protocols by considering different parameters. A comparison of the performance of E-OCER with OCER is made to study the effect of on-body sensors communication on the energy consumption and throughput of the network. This paper also provides a comprehensive energy model to calculate the total energy consumption of the network. In addition to the radio transmission and receiving energy, other basic energy consumption sources viz. processing energy, sensor sensing, transient energy and transmission/reception on/off energy have also been taken into account. The results show an improved performance of the proposed protocols in terms of energy efficiency.

1. Introduction

The development of wireless sensors has revolutionized the health management and offered step-changing improvements. These sensors communicate with each other and form a Wireless Body Area Network (WBAN), a promising technology for healthcare applications. It provides professional healthcare services to its users on a continuous basis without having to live at or near hospital. It also facilitates the management of emergency situation in a better way.

According to Administration on Aging, there is a progressive rise in people living longer and increasing segment of the elderly population that will inevitably be afflicted with chronic conditions. This is expected to place more stress on the already taxed healthcare industry. This means more the older people there are, the greater is the need for the technically better ways to monitor their medical status and keep them safe without forcing them to live at or near a hospital. WBAN hold great promise to expand the capabilities of healthcare system for elderly people.

To make this technology ubiquitous, several challenging issues need to be addressed [1]. These challenges include limited node energy, Quality of Service (QoS) requirements (data delivery delay and reliability), dynamic network topology, heterogeneous data generation rate, low transmit power due to concerns on health hazards which necessitates for careful resource management [2].

Energy management plays a pivotal role to increase the network lifetime as energy resources in WBAN are limited [3]. Direct communication between source nodes and sink nodes consume additional energy due to short communication range and high path loss in WBANs. More is the energy consumption, lesser will be the network lifetime [4]. The multihop communication routes data with the assistance of intermediate nodes but puts more constraints on the energy dissipation of the forwarder nodes [5]. The routing mechanism should take the merits of both types of communication. The routes need to be discovered when there is a request for it. The routing mechanisms will affect the end-to-end path reliability and overall energy consumption of the network. In the literature several mechanisms have been proposed that focus on the im-

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provement of energy efficiency by using appropriate routing mechanisms. Due to distinctive BAN characteristics, existing energy efficient and QoS aware routing protocols of Wireless Sensor Networks (WSNs) cannot be used directly for communication [6]. Generally, the number of nodes in BAN is limited to a few dozen as compared to WSN, where there is a wide variation from as few as a dozen to as large as several thousands. WBAN has a low transmission range of sensors limited to the height of the human body due to which the intra-BAN communication is usually restricted within a few meters; whereas WSN spans a large area from 100 m or a few kilometers. In WBANs, due to its asymmetric network [7], at least one node with more processing power and power supply acts as body coordinator taking over energy-consuming tasks from the low-power sensor nodes. The sensor nodes in BAN are tiny in size as compared to the nodes used in WSN. This is one of the major causes of resource limitations. The limitations of BAN nodes include lower bandwidth, low energy source, slower processing speed, and smaller memory as compared to the WSN node. Since mobility is an integral characteristic of a BAN, therefore, BAN nodes share the same mobility pattern whereas WSN nodes that are usually considered fixed. In case of WSN, data loss can be compensated with the use of redundant nodes whereas it becomes more significant and may require additional measures to ensure QoS and real time delivery in WBANs. For the efficient functioning of Body Area Networks, it is critical to obtain minimal energy consumption with the required level of reliability as data to be communicated is important. Therefore, innovative techniques for route selection between data packets are highly required.

This paper proposes two energy aware protocols namely Optimized Cost Effective and Energy Efficient Routing Protocol (OCER) and Extended-OCER (E-OCER) for ordinary data packets that determines optimized selection of forwarder node based on a multiple objective cost function using Genetic Algorithm.

The performance of OCER is evaluated and compared with Energy-aware Peering Routing Protocol for indoor hospital Body Area Network Communication (EPR) [8] and Data Centric Multi-objective QoS-Aware Routing Protocol (DMQoS) [6] from literature. EPR and DMQoS protocols didn't consider the inter-node communication that collects the patient's vital information and forwards the data to the body coordinator. This communication is highly energy constrained as the sensor nodes are equipped with limited batteries. The proposed protocol E-OCER considers the inter-node communication on the patient's body, the nodes forward the data to the body coordinator in an energy efficient manner. The proposed routing protocols have been evaluated based on comprehensive simulations using MATLAB in terms of energy consumption, throughput and number of packets forwarded. Results obtained demonstrate that the proposed protocols a) are providing better results in terms of chosen parameters b) Use of Genetic algorithm for optimizing multiobjective parameters to select the forwarder node has been instrumental in providing better results instead of direct selection.

The rest of the paper is organized as follows. In Section 2, some state-of-the-art works and their limitations are discussed. The network model and the proposed routing protocols are discussed in Section 3. Section 4 presents the performance evaluation and discussion of results. Section 5 concludes the paper.

2. Related work

This section presents the related work carried out by various researchers over the last decade. A concise overview of the various categories of existing routing protocols in WBAN is presented below.

1. Temperature-Aware Routing Protocols. The rise in temperature on human body for a WBAN can be attributed to several reasons such as power consumption by the nodes circuitry [9], antenna radiation absorption that needs to be controlled to avoid damage to human tissues in the long run. In order to reduce the rise in temperature in sensors, several temperature aware routing protocols have been proposed in literature. Thermal-aware Routing Algorithm for implanted sensor networks (TARA) [9], Least Temperature Routing (LTR) and Adaptive Least Temperature Routing (ALTR) [10], Hotspot Preventing Routing (HPR) algorithm [11], least total-route-temperature (LTRT) protocol [12] Routing Algorithm for Network of Homogeneous and ID-Less Bio-Medical Sensor Nodes (RAIN) [13], Thermal-Aware Shortest Hop Routing (TSHR) [14] provide better packet delivery ratio by reducing the rise in temperature and packet delay.
2. Qos Aware Routing Protocols. Qos Aware Routing Protocols are based on a modular framework that utilizes different kinds of modules for communication using different QoS parameters. A QoS-aware Routing Service Framework for Biomedical Sensor Networks [15], Reinforcement Learning based routing protocol with QoS support [16], LOCALized Multi-Objective Routing (LOCALMOR) [17], Razzaque et al. proposed a data-centric multiobjective QoS-Aware routing protocol (DMQoS) [6], which categorized a data packet into delay and reliability modules. A different routing technique is then applied to each moduler. DMQoS protocol is designed for the communication between the coordinators. Hello packets are used to broadcast the information of a node to its neighbor nodes. This broadcast of hello packets increases network traffic which results in higher BAN energy consumption. As the next hops, DMQoS considers only BAN Coordinators in BAN communication. But in a hospital environment, since there are different requirements for different patients, therefore BAN communication has to take place through different device types as next hops. Although delay and bit error rate have improved significantly but at the cost of increased energy consumption which decreased the overall network lifetime. Both QoS-Aware Peering Routing for Reliability-Sensitive Data (QPRR) [8] and QoS-Aware Peering Routing for Delay-Sensitive Data (QPRD) [18] lower energy consumption; the former improves reliability whereas the latter results in lesser delay.
3. Postural-Movement-Based Routing Protocols Postural movements in WBAN leads to problems like partitioning. Postural-Movement based protocols use cost function based techniques in which data is forwarded to the path with the minimum cost from source to the sink. This helps to solve the problem of disconnections due to human movements. On-Body Store and Flood Routing (OBSFR) [19] reduces packet delivery delay, Probabilistic Routing (PRPLC) [20] reduces end to end delay.
4. Energy Aware Cost Function based Routing Protocols.
These protocols propose a multiobjective cost function to select the forwarder node and the one with minimum value of cost is selected. For solving routing and energy problems, two approaches have been employed by researchers; either minimizing the energy consumption of any single node in the network, or minimizing the average energy consumption over all nodes. iM-SIMPLE [21] utilizes the concept of multi-hop communication to minimize the total energy consumption of the network. The forwarder node is chosen with minimum value of the cost function having residual energy and distance as parameters. Choosing the next hop with maximum residual energy balances the energy consumption among the sensor nodes and the least distance reduces the path loss and hence improves the packet delivery ratio of the network. Co-leeba [22] exploits the merits of both single-hop and multi-hop routing to route the

data. The communication link with minimum pathloss is chosen. The cost functions based on residual energy information and distance are introduced to learn and select the most appropriate route. The concept of cooperative learning avoids redundant transmissions and helps in achieving the objectives. Energy Efficient Thermal and Power Aware Routing Protocol (ETPA) [23] is another cost based routing protocol which finds an efficient route based on minimum cost. In case, it finds a feasible route, it stores the packets. The packets are stored for a duration of two frames, after which they are dropped. A packet is also dropped if it did not reach its destination within the specified number of hops. This helps in reducing the delay in the network. Khan et al. [24] proposed a novel BAN network architecture for indoor hospital scenario, and a new Energy-aware Peering Routing protocol (EPR). EPR addressed the shortcomings of the DMQoS protocol with the consideration of all possible devices as Nursing Station Coordinator (NSC), Medical Display Coordinator (MDCs) and Body Area Networks (BANs) in the hospital environment by controlling the broadcasts of the Hello packets.

The proposed work has taken similar network model as EPR and introduces a multi-objective cost function optimized using Genetic Algorithm to select the forwarder node. Based on this, energy efficient and reliable routing mechanisms have been proposed for processing the vital information with optimal criteria and similar scenarios as that of EPR are taken for the performance evaluation of proposed techniques.

3. Materials and methods

3.1. WBAN design model

This section presents the proposed WBAN optimization framework based on [8], the pathloss model, link reliability and the energy model to calculate the total energy consumption. A cost function is proposed to represent the problem and a multiobjective optimization technique is applied on the proposed model. The proposed model (i) optimally finds the best solution for proposed scenarios, and (ii) studied and evaluated the effect of network parameters on the solutions thus obtained.

3.1.1. Network model

In this paper, we consider a hierarchical WBAN hospital scenario having three communication tiers as shown in Fig. 1. Tier 1 deals with “intra-BAN communication” which constitutes the patient with various diseases diagnosed by a sensor network on the body. The communication can be among the body sensors using point-to-point (P2P) links for establishing multihop path as well as the communication between body sensors and the BC. The sensors with equal power and communication capabilities forward the data to the BAN Coordinator (BC) which acts as a cluster head. It is assumed that the position of biosensors is fixed and have the same transmission range, nevertheless, the body movements and moving parts will result in change the distance values between various bio-sensors. Tier 2 is an “inter-BAN communication” between the BC and one or more PDDs. The Tier 2 device known as Patient Data Display (PDD) is the possible next hop for the BC. The PDD forwards BAN data to Tier 3 communication device known as Centralized Display Device (CDD).Tier 3 is “beyond-BAN communication” which enables the authorized healthcare professionals to access the patient’s data remotely using Internet. This contributed to the further enhancement of the application and coverage range of E-healthcare system.

The CDDs are directly connected to a power source. The PDDs use consumable batteries and the BCs have limited energy availability. For intra-BAN and inter-BAN communication, Zigbee network is used. For beyond-BAN communication, Internet/wifi/cellular networks are used.

Table 1
Notation.

Notation	Meaning
N	The number of sensors
ID_d	ID of the destination device
L_d	Location of the destination
ID_k	ID of neighbor node
$dist_{k,\,d}$	Distance from neighbor node k to the destination node d
E_k	Residual energy of the node k
PL_k	Pathloss from source node to the node k
$Link\,R_k$	Link reliability between the nodes s and k
$dist_{s,\,k}$	Distance from source node to neighbor node
$dist_{s,\,d}$	Distance from source node to destination node
C_k	Link cost between nodes s and k
X_s, Y_s	X, Y coordinates of node s
X_k, Y_k	X, Y coordinates of node k
X_d, Y_d	X, Y coordinates of node d
E_{max}	Maximum available energy at each nodes
NT	Neighbor Table
HP	Hello Packet
PL_{max}	Maximum pathloss
$Link\,R_{max}$	Maximum reliability
nh_0	Next hop node

Let $S = S_1, S_2, \cdots, S_N$ denote the sensor set. A wireless link can be established by each node in the sensor set with any other node in the set if it is placed within the radio range. The basic notations used in this study are summarized in Table 1:

3.1.2. Propagation model

Path loss is defined as a reduction in the power density of electromagnetic waves. This paper focuses on the on-body propagation model and the pathloss equations of [25]. In the on-body propagation model, communication between sensors placed on the body can take place when the transmitted signals propagate through the body, diffract around the body or reflected off by nearby distractions and then back at the body. The two predominant factors that affect the value of pathloss in case of WBANs are distance and frequency.

The Friis formula in free space is used for calculating the path loss PL_d, which depends on the distance d between two communicating nodes and is given in Eq. (1):

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) \tag{1}$$

where $PL(d_0)$ is the path loss in dB at a reference distance d_0 and is calculated using Eq. (2) and n is the path loss exponent considered as 2 in free space and vary in different body locations. The average path loss model of the whole body has been chosen with its parameters $d_0 = 10$ cm and $PL(d_0) = 35.2$ dB.

$$PL_{d_0} = 10 * \log(4\pi \cdot d_0 f) * c \tag{2}$$

Here, f the frequency of operation, and c is the speed of light.

The body movements and moving parts cause variation in the value of path loss due to change in distance between the various biosensors. The path loss may deviate from its mean value, and this phenomena is called shadowing. A static body may also get affected due to shadowing. In the current model, it is assumed that path loss and shadowing affect the link between two nodes. Giving due consideration to the shadowing factor, the total path loss may be given by Eq. (3):

$$PL = PL(d) + X_\sigma \tag{3}$$

Here, X_σ is a shadowing factor in dB, which is a Gaussian-distributed random variable with zero mean and a standard deviation, σ [26].

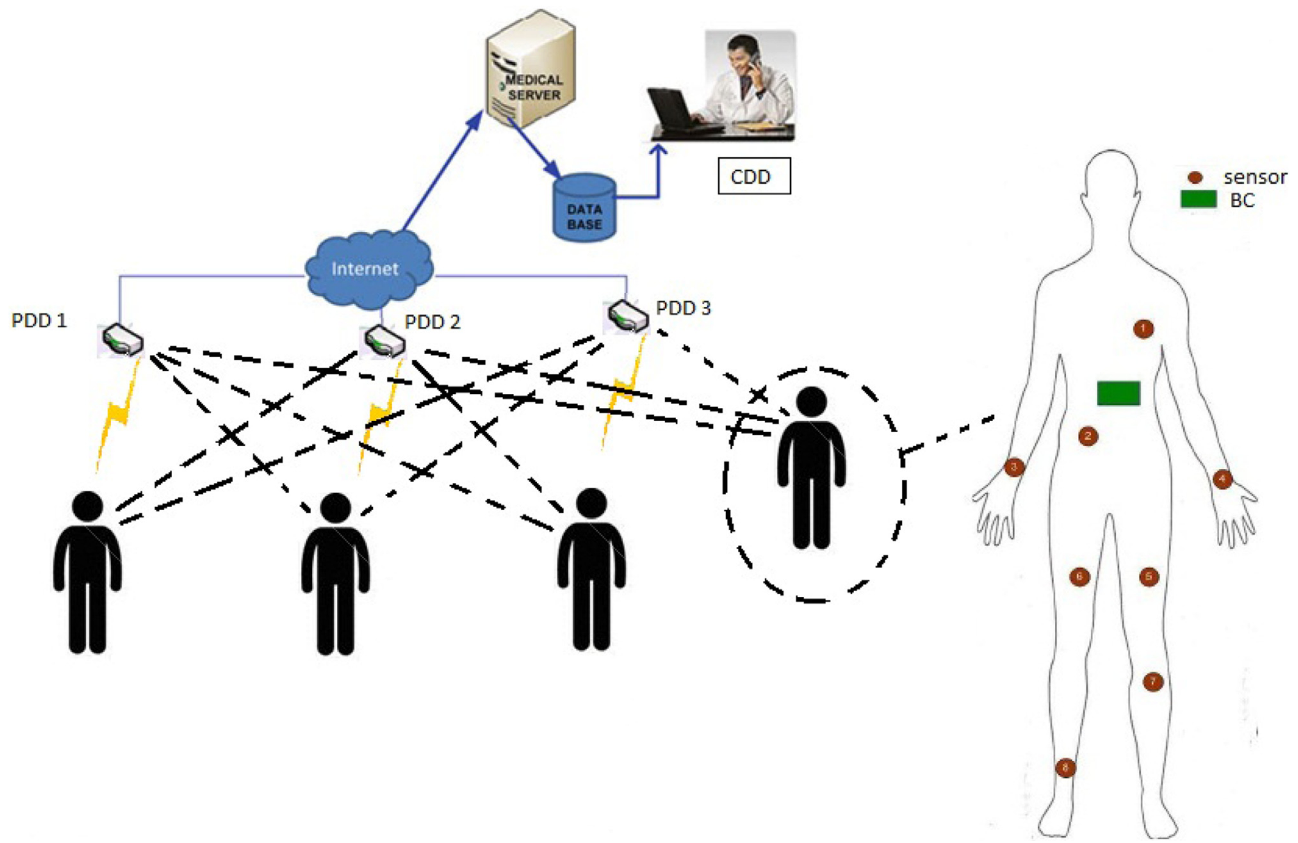


Fig. 1. WBAN communication system.

3.1.3. Energy model

In WBANs, nodes communicate at an expense of a large amount of energy consumption. The total energy consumption is the sum of the processing energy, sensing energy, transient energy and transmission/reception on-time energy and energy dissipated by the data transmission and reception of biosensors attached to the body and the body coordinators. The energy consumption for all processes of every sensor node are same as all regular sensor nodes (except BCs) are assumed to be homogeneous. The BC uses more transmission and receiving energy as compared to the ordinary sensor node due to the additional data processing and aggregation activities that it performs. A weighting factor $w_i > 1$ is applied to account for the more energy consumption than a regular sensor node [27,28]. All parameter values used in the energy model are listed in Table 2.

a. Sensor Sensing

A sensor node is able to connect to the physical world because of its sensing system. Considering I_{sens} as the total current needed for sensing and T_{sense} as the time taken for sensing the sensor node, the total energy consumption for sensing task for n bit packet, E_{sens_N} at the sensor node per round is calculated as given in Eq. (4):

$$E_{sens_N}(n) = nV_{sup}I_{sens}T_{sens} \tag{4}$$

and the total energy consumption for sensing task at the BC per round by

$$E_{sens_{BC}}(w_1, n) = w_1 E_{sens_N}(n) \tag{5}$$

where V_{sup} is the supply voltage.

b. Radio Transmission and Receiving

If the energy dissipated by the radio in order to run the transmitter circuitry is represented by E_{TXelec}, the energy dissipated by the receiver is represented by E_{RXelec}, the energy for transmitter amplifier as E_{amp}, the distance between nodes i and j as D_{ij} then the energy consumption due to transmit of n bit packet from sensor node to BC per round can be calculated by Eq. (6). Energy dissipated when n bit packet is received from sensor node is given by Eq. (7).

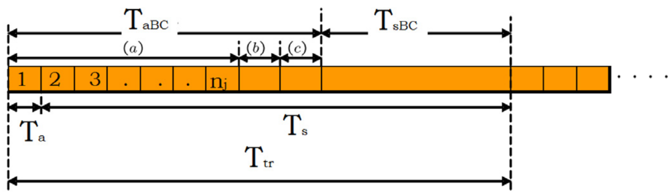
$$E_{TXelec}(n, D_{ij}) = nE_{TXelec} + nE_{amp}D_{ij}^{p_{ij}} \tag{6}$$

$$E_{RXelec}(n) = nE_{RXelec} \tag{7}$$

Therefore, energy dissipated when n bit packet is transmitted to a distance D_{ij} from the BC per round can be estimated by Eq. (8), whereas the energy dissipated when n bit packet is re-

Table 2
Parameter values used in the present energy model [27].

Symbol	Description	Value
N_{cyc}	Number of clock cycles per task	0.97×10^6
C_{avg}	Avg. capacitance switch per cycle	22 pF
V_{sup}	Supply voltage to sensor	2.7 V
f	Sensor frequency	191.42 MHz
I_0	Leakage current	1.196 mA
n	Transmit packet size	2 kb
E_{TXelec}	Energy dissipation: electronics	50 nJ/bit/m^2
E_{amp}	Energy dissipation: power amplifier	100 pJ/bit/m^2
T_{tranON}	Time duration: sleep idle	2450 s
$T_{tranOFF}$	Time duration: idle sleep	250 s
I_A	Current: wakeup mode	8 mA
I_S	Current: sleeping mode	1 μA
T_a	Active time	1 ms
T_s	Sleeping time	299 ms
T_{tr}	Time between consecutive packets	300 ms
V_t	Thermal voltage	0.2 V
T_{tr}	Time between consecutive packets	300 mS
T_{sens}	Time duration: sensor node sensing	0.5 mS
I_{sens}	Current: sensing activity	25 mA



(a) time to receive packets from its own n_j sensors
(b) time to receive packets from child BCs
(c) time to transmit packets to parents BCs

Fig. 2. The sensor nodes and BCs wake-up and sleeping times per round.

ceived from BC is estimated by Eq. (9).

$$E_{TXelec}(w_2, n, D_{ij}) = w_2 n E_{TXelec} + n E_{amp} D_{ij}^{p_{ij}} \tag{8}$$

$$E_{RXelec}(n) = w_2 n E_{RXelec} \tag{9}$$

where n is the total number of bits transmitted/received and p is the distance based pathloss exponent.

c. Processing Energy
Most of the energy consumed for processing and aggregation of data is accorded by the consumption of energy during switching (E_{switch}) and energy consumption due to leakage current E_{leak}.
Total energy consumed in data processing/aggregation of n bit packet by the sensor node, E_{proc_N}, per round is given by:

$$E_{proc_N}(n, N_{cyc}) = nN_{cyc}C_{avg}V_{sup}^2 + nV_{sup}\left(I_0 e^{\frac{V_{sup}}{k_p V_t}}\right)\left(\frac{N_{cyc}}{f}\right) \tag{10}$$

and total energy dissipated by the body coordinator (BC) per round is given by

$$E_{proc_{BC}}\left(w_3, n, N_{cyc}\right) = w_3 E_{proc_N}\left(n, N_{cyc}\right) \tag{11}$$

where I_0 is the leakage current, V_t is the thermal voltage, f is sensor frequency, C_{avg} is the average capacitance switched per cycle, N_{cyc} is the number of clock cycles per task and k_p is the constant that depends on the processor. Assuming that sensor nodes only sense data and transmit to their BC once during each round, the energy dissipation due to data processing from from regular sensor nodes is ignored [27].
As per [27], it is considered that the sensing energy of BC is 10 % more than that of normal sensor nodes whereas the processing and communication energy of the BANC is 20 % more than normal sensor nodes. Hence, the weighting factor, w_i has been assumed as $(w_1, w_2, w_3) = (1.1, 1.2, 1.2)$

d. Transient Energy
Transitions between different modes (active, idle and sleep) of radio and micro-controller units consume a significant amount of power while accounting for the total energy consumption of the network. These are often not considered in the literature. Let the time taken for the transition from sleep-to-idle mode be T_{tranON} and the time needed for the transition from idle-to-sleep mode by $T_{tranOFF}$. A sensor node will listen to a busy channel, wake up for T_a duration and then sleeps for T_s, assuming $T_s \gg T_a$. Similarly, BC wakes up for $T_{a_{BC}}$ duration, and then sleeps for $T_{s_{BC}}$. Let the time between corresponding packet transmissions be T_{tr}. The BC will transmit every packets it receives in one batch after every T_{tr} seconds (Fig. 2) as given below.

$$T_{tr} = T_{a_{BC}} + T_{s_{BC}} = T_a + T_s \tag{12}$$

Let D_N be the duty cycle for the sensor node [29]:

$$D_N = \frac{T_{tranON} + T_a + T_{tranOFF}}{T_{tranON} + T_a + T_{tranOFF} + T_s} \tag{13}$$

Similarly, let D_{BC} be the duty cycle for BC:

$$D_{BC} = \frac{T_{tranON} + T_{a_{BC}} + T_{tranOFF}}{T_{tranON} + T_{a_{BC}} + T_{tranOFF} + T_{s_{BC}}} \tag{14}$$

The average current for a sensor node is defined as:

$$I_N = D_N I_A + (1 - D_N) I_S \tag{15}$$

The total energy consumption by the sensor node per round is calculated by

$$E_{tran_N} = T_a V_{sup}[D_N I_A + (1 - D_N) I_S] \tag{16}$$

where I_A and I_S are current for active and sleeping mode.
Thus, the average current for BC is given by

$$I_{BC} = D_{BC} I_A + (1 - D_{BC}) I_S \tag{17}$$

The energy consumption due to performing nodes at the BC per round is

$$E_{tran_{BC}} = T_{a_{BC}} V_{sup}[D_{BC} I_A + (1 - D_{BC}) I_S] \tag{18}$$

e. Transmission/Receiver on-time (Start-up time, T_S)
The time needed by a sensor node to attain a steady state after the power is switched on is known as the startup time (T_s). It is an established factor in the power management of sensors. The process will receive a wrong value, if the sensing activity does not wait for the (T_s) after the micro controller unit requests the sensor to turn on [28].

3.1.4. Reliability model

Real time applications for WBAN are sensitive to packet loss. Networks often attempt link-level retransmissions to minimize the link level packet loss and to avoid the end-to-end throughput degradation. More is the link reliability of the nodes, more is the network reliability. The exponentially weighted moving average (EWAD) is used to calculate the link reliability between two nodes ($Link\,R_{sk}$) given by Eq. (19) [30].

$$Link\,R_{sk} = (1 - \gamma) Link\,R_{sk} + \gamma \frac{Tx_{succ,sk}}{Tx_{tot,sk}} \tag{19}$$

where $Tx_{succ,sk}$ is the total number of packets transmitted successfully between node s and node k, $Tx_{tot,sk}$ is the total number of times the transmission and retransmission attempts have been made for all packets and γ is the average weighting factor. The best suited value of γ for our simulations is 0.4. The probability for error of the various links can be evaluated by using Eq. (20):

$$P_{error} = 1 - Link\,R_{sk} \tag{20}$$

3.2. A multiobjective optimization problem

The proposed work has tried to investigate the routes followed by the nodes to transmit data from source node to the sink in order to meet the specific requirements keeping in consideration the goal of energy consumption minimization by the network.

The performance is analyzed based on the overall energy consumption, the number of packets forwarded and throughput achieved. The results reflect the optimization of the network in terms of energy efficiency. This proposed work exploits a cost function to elect an optimized forwarder node. There are three weights w_1, w_2 and w_3 to provide the relative importance of the three parameters (residual energy, pathloss and link reliability) within the proposed cost function. The range of weights is determined based on the experiments. Changing these parameters lead to different values of the cost function. The weights are optimized using iterative process of Genetic Algorithm.

Minimize:

$$Cost = w_1 \times \left|\frac{E_{max} - E_k(NT)}{E_{max}}\right| + w_2 \times \left|\frac{Link\,R_{max} - Link\,R_k(NT)}{Link\,R_{max}}\right| + w_3 \times \left|\frac{PL_{max} - PL_k(NT)}{PL_{max}}\right| \tag{21}$$

Table 3
Parameter setting of GA.

GA parameter	Value	Description
Maximum iterations	10	The successive iterations no longer produce better results
Population size	20	Number of chromosomes in population (in one generation)
Selection strategy	Roulette Wheel	Method used to select the best chromosome
Crossover operator	Uniform	Each gene in the offspring is copied from the same gene from one of the two parents with the same probability
Crossover rate	0.7	Should be high
Mutation operator	Binary swap	Value of selected gene is complemented

subject to:

$$w_1 + w_2 + w_3 = 1 \tag{22}$$

where

$$0.5 < w_1 < 1.0 \tag{23}$$

$$0 < w_2 < 1 - w_1 \tag{24}$$

$$w_3 = 1 - w_1 - w_2 \tag{25}$$

The next hop node with the minimum value of cost is elected for sending data. Different parameters used for GA are given in Table 3.

3.3. Cost effective energy efficient network model

A network model for efficient routing of important data from the sensors to the destination nodes is required. The goal is to minimize the overall energy consumption of network.

3.3.1. Optimized cost effective energy efficient routing protocol

(OCER) The proposed cost-effective and energy-efficient routing protocol is explained below:

a. Initialization Phase

PDDs and CDD which have considerably more energy than BAN nodes broadcast Hello packets periodically and BAN broadcasts Hello packets at the reception of other nodes' Hello packets containing PDD or CDD information to construct and maintain a neighbor table and finally a routing table. It is assumed that node k, the neighbor node of node s, is located between source node s and destination node d(BANC). The Hello packet fields of node k are ID_d, L_d, ID_k, E_k, PL_k and $Link\,R_k$.

When the node s receives hello packets from node k, it will record the information in its neighbor table. Furthermore, the node s adds its own information for broadcasting in the received Hello packet. The $dist_{k,\,d}$ is calculated by using Eq. (26).

$$dist_{k,d} = \sqrt{(x_k - x_d)^2 + (y_k - y_d)^2} \tag{26}$$

The neighbor table structure fields of node s are ID_d, ID_k, $dist_{s,k}$, $dist_{k,d}$, E_k, PL_k, $Link\,R_k$ and C_k. Algorithm 1 presents the procedures for the construction and updation of a neighbor table at every node s. The neighbor table constructor algorithm is invoked when a hello packet is received by a node s from node k. It will add the neighboring node to the neighbor table (NT) if the neighboring node is closer to the destination d.

PL_k, $Link\,R_k$, C_k and $dist_{s,k}$ are calculated by using Eqs. (3), (19), (21) and (26) respectively. The communication cost (C_k) is calculated using the values of PL_k, $link\,R_k$ and E_k. The best next hop will be the node k with minimum value of C_k.

b. Routing Algorithm

The proposed routing table algorithm filters the neighbor table having many records for the same destination, and only chooses the one with the least value of communication cost. The routing table fields of sensor node s are ID_d, L_d and nh_o. As shown in Algorithm 2, if the destination d and node s are one hop apart, the next hop (nh_o) will be the destination ID (ID_d). If they are far apart, then the neighbor node k having minimum value of communication cost (C_k) will be selected as next hop.

Algorithm 1 Neighbor table constructor algorithm at each node s.

Input: Hello Packet (Node s receives hello packet from neighbor node k)

if $dist_{k,d} < dist_{s,d}$ **then**
  (add a new record for d's information in the neighbor table)
  $ID_d(NT) \leftarrow ID_d(HP)$
  $ID_k(NT) \leftarrow ID_k(HP)$
  $dist(s,k)(NT) \leftarrow dist(s,k)$
  $dist(k,d)(NT) \leftarrow dist(k,d)$
  $E_k(NT) \leftarrow E_k(HP)$
  $PL_k(NT) \leftarrow PL_k(HP)$

$$C_K(NT) = w_1 \times \left|\frac{E_{max} - E_k(NT)}{E_{max}}\right| + w_2 \times \left|\frac{Link\,R_{max} - Link\,R_k(NT)}{Link\,R_{max}}\right| + w_3 \times \left|\frac{PL_{max} - PL_k(NT)}{PL_{max}}\right|$$

else
  (add a new record for the neighbor node k's information in the neighbor table)
  $ID_d(NT) \leftarrow ID_d(HP)$
  $ID_k(NT) \leftarrow ID_k(HP)$
  $dist(s,k)(NT) \leftarrow dist(s,k)$
  $dist(k,d)(NT) \leftarrow 0$
  $E_k(NT) \leftarrow E_k(HP)$
  $PL_k(NT) \leftarrow PL_k(HP)$

$$C_K(NT) = w_1 \times \left|\frac{E_{max} - E_k(NT)}{E_{max}}\right| + w_2 \times \left|\frac{Link\,R_{max} - Link\,R_k(NT)}{Link\,R_{max}}\right| + w_3 \times \left|\frac{PL_{max} - PL_k(NT)}{PL_{max}}\right|$$

end if

3.3.2. Parameter setting and configuration

The various network parameters used in the simulations are listed in Table 4:

3.3.3. Extended-OCER

The OCER is intended for a communication from body coordinator ($BC1$, $BC2$, $BC3$, $BC4$) to CDD through Patient Data Display ($PDD1$, $PDD2$, $PDD3$). OCER model comprises of only 8 nodes. In OCER, Body Coordinator sends data to best next hop PDD as selected using the proposed cost function. After that, PDD sends data directly to CDD. However, E-OCER involves 4 BANs with 8 sensor nodes ($S1$, $S2$, $S3$, $S4$, $S5$, $S6$, $S7$, $S8$) and one BC on each BAN. Therefore, E-OCER model is a network of 40 nodes. E-OCER extends the work of OCER by including the communication between

Algorithm 2 Routing table constructor algorithm.

Input: Neighbor table $NH_{s,d} \forall d \in (sensor\ nodes, BANC)$
for each $d \in (sensor\ nodes, BANC)$ **do**
  $nh =$ `all neighbor nodes` $k \in nh_{(s,d)}$
  Add all neighbor nodes k to neighbor table entry of s
  if ($nh == 1$) **then**
    $nh \leftarrow nh_0$
  else
    if $nh > 1$ **then**
      $nh_0 \leftarrow$ `node` $k \in nh$ `with minimum` C_k
    end if
  end if
end for

Table 4
Network parameters.

Parameters information	Value
Area	9 m × 9 m
Type of deployment	Case 1 and Case 2: Each node is fixed Case 3: PDD and CDD are fixed, BANs are movable
Number of nodes	4 BANs, 3 PDDs, 1 CDD
Initial node locations	CDD(0,1), PDD1(0, 5), PDD2(0, 3), PDD3(1, 3), BC1(2, 3), BC2(3, 5), BC3(3, 0), BC4(6, 3)
Initial node energy (E_i)	Normal Node: 18, 700(mJ) BAN Coordinator: 20, 570 (mJ)
Transmit power	Different Transmission Power (−25 dBm, −15 dBm, −10 dBm)
Reception power	7 dBm
Traffic type	CBR
Packet size	32 bytes
MAC protocol	IEEE 802.15.4

Table 5
Location of bio-sensors on patients' body [22].

Node no	x coordinates(m)	y coordinates(m)
1	0.2	1.2
2	0.6	1.1
3	0.7	0.8
4	0.5	0.6
5	0.1	0.8
6	0.3	0.5
7	0.5	0.3
8	0.3	0.1
BC	0.4	0.9

on-body sensor nodes which has not been taken into account in OCER. Since bio-sensors in inter-BAN are most energy constrained, this paper is an attempt to implement the energy aware routing mechanism at Tier 1 to account for the total energy consumption of the network. The Algorithms 1 and 2 as proposed for OCER have been implemented for routing in E-OCER as well. Data transmission takes place in a multi-hop fashion. Bio-sensor on the path route with minimum value of cost as calculated by the proposed cost function implied in Algorithm 1 is selected for data transmission. Since E-OCER involves sensor nodes communication on human body, which is a more obstructed environment, the value of pathloss increases. Due to this, the network connectivity decreases gradually. Therefore, multi-hop communication is the only alternative for such scenarios wherein the sensor nodes behave as intermediate nodes for data propagation from source node to sink node. Extended-OCER is analyzed in terms of energy consumption, throughput and the total packet forwarded. To validate the performance of Extended-OCER, it is compared with the first proposed protocol OCER.

3.3.4. E-OCER network topology and parameter setting and configuration

In Extended-OCER, the Body Coordinator is located at the waist. Four patients are considered for the simulation experiments. Each patient has eight bio-sensors deployed on his body with coordinates as shown in Table 5. Initial energy of Body-coordinators is more than normal nodes as mentioned in Table 4. The network parameters are also given in Table 4.

4. Results and discussion

In order to calibrate the controllable parameters of GA, an iterative process is followed for evaluating different values for each parameter in order to find the best parameter from the population. In the experiments, the maximum number of iterations in GA has been set to 10 and the population size of chromosomes has been set to 20. A comparison of the simulation results of OCER is made with EPR and DMQoS using MatLab simulator for 3 different scenarios to illustrate the effectiveness of OCER in terms of energy consumption. Along the same lines, a comparative analysis of E-OCER is performed with OCER for the same three scenarios in order to show the influence of on-body biosensors on the overall energy consumption of the network. In Scenario 1, a fixed number of packets are sent and all nodes are static; in Scenario 2, a variable number of packets are sent and all nodes are static; and in Scenario 3, a variable number of packets are sent and the BANs are movable (this is to model patient mobility). The results are then observed and compared.

Table 6
Energy consumption comparison.

Transmit power(dBm)	OCER(mJ)	EPR(mJ)	DMQoS(mJ)
−25	6498	9390	9474
−15	6512	9340	9536
−10	6573	9380	9588

4.1. Comparison of OCER with other methods

Comparative analysis of the performance of the proposed protocol OCER is done with EPR and DMQoS based on simulations. In case of DMQoS, each coordinator is placed in 63.3 m × 63.3 m = 4000 m^2 area within the total area of 2000 m × 2000 m = 4,000,000 m^2. Since the proposed work is focusing on an indoor-hospital environment, such dimensions are not feasible for the same. The network parameters used in the simulation are similar to EPR and are shown in Table 3. In the present work, the CDD, PDDs and BANC are placed within the prescribed area of 9 m × 9 m = 81 m^2. In order to carry out the performance evaluation, three different values of transmit power (−10 dBm, −15 dBm and −25 dBm) are used in the simulations. The overall energy consumption in the network is shown in Table 6:

4.1.1. Scenario 1: fixed number of packets (1000 packets) are sent and all nodes are static

In this case, each BANC transmits a total of 1000 data packets to the corresponding PDD or CDD. Fig. 3 depicts the location of the nodes involved in communication. BC_1 is deployed near to the PDDs and CCD. DMQoS forwards all the data packets received from other nodes through BC_1 to PDDs or CDD, which resulted in more energy dissipation for BC_1. In case of EPR, BC_1 transmits packets to PDD_1, BC_2 sends packets to PDD_2, BC_3 sends packets to PDD_3 and BC_4 transmits packets through another BC to reach PDD and finally to CDD. Since BC_4 is not peered with any specific PDD, therefore, its data route through the intermediate nodes to reach CDD. Although EPR chooses the most appropriate next hop based on the lowest value of communication cost to solve DMQoS problem to send its packets to the destination node, still majority of the data packets are sent directly due to peering of BANCs with the CDDs. In the OCER scheme, a cost function optimized using Genetic Algorithm is applied to the neighbor nodes and the node with minimum value of cost function is chosen as the forwarder node in order to achieve maximum energy savings and to balance the residual energy in the network. This reduces the overall energy consumption from EPR by 28–29% for all the three transmission powers of −25 dBm, −15 dBm and −10 dBm as shown in Fig. 4.

Fig. 5 shows the values of packet forwarded by intermediate nodes. It is seen from the figure that 2526, 3922, and 3849 packets are forwarded by intermediate nodes in DMQoS for the transmit powers of −25 dBm, −15 dBm and −10 dBm respectively as DMQoS sends the data packets to the closest neighbor node. In case of EPR, when the transmit power is −25 dBm, 332 data packets go through the intermediate nodes. For transmit power

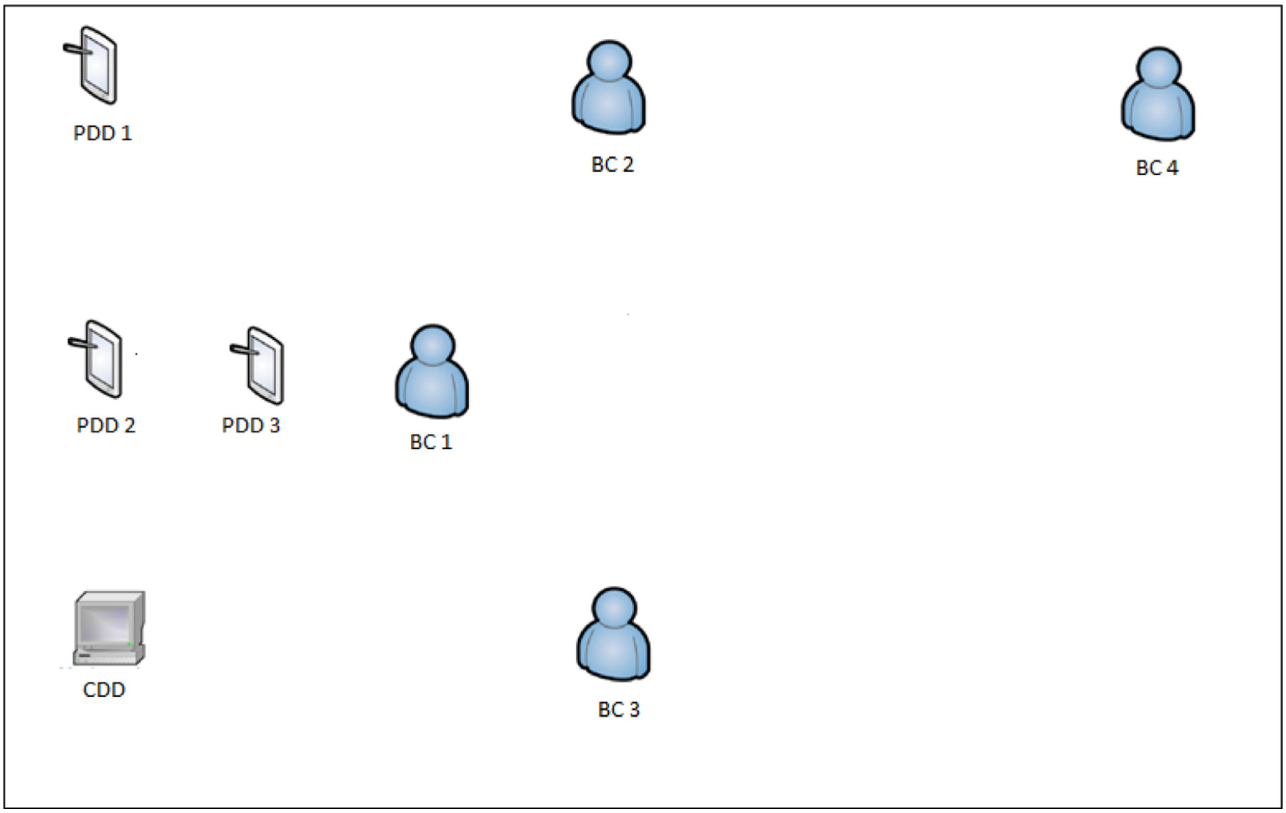


Fig. 3. Communication Scenario.

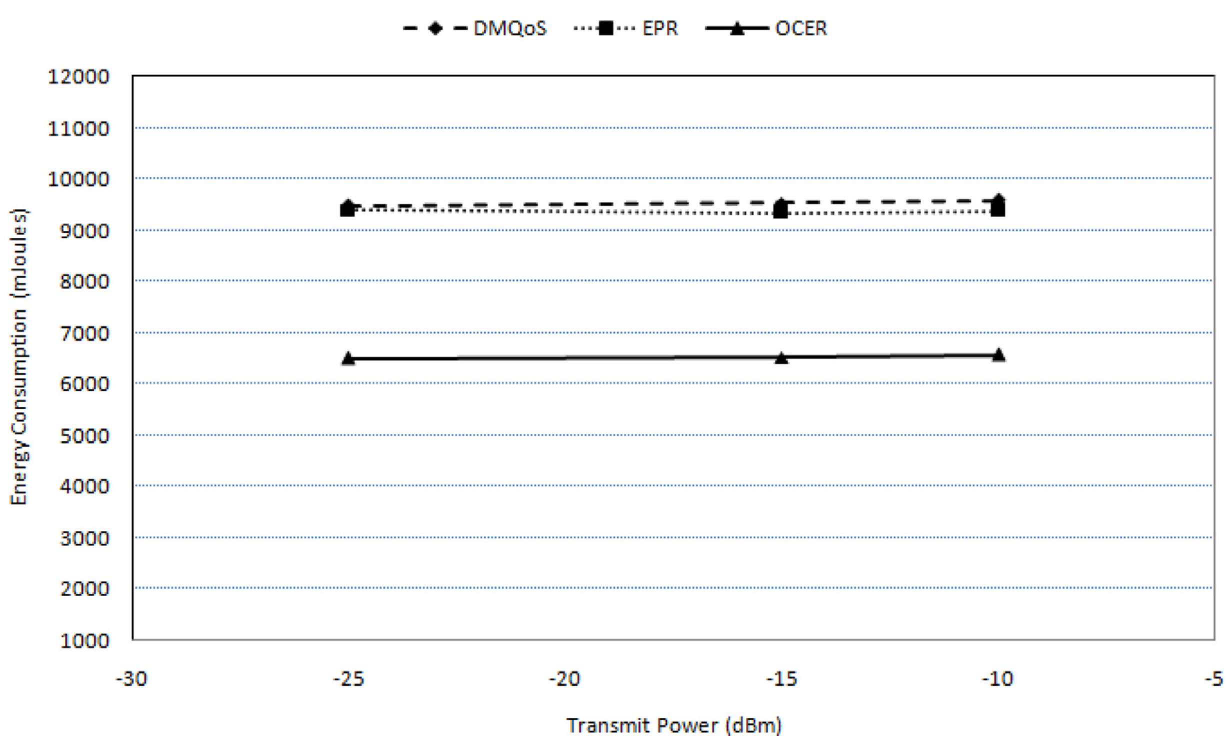


Fig. 4. Overall energy consumption.

of −15 dBm and −10 dBm, no packet goes through intermediate nodes in EPR as the destinations are in range due to the high transmit powers. The BANC in EPR sends data to another BANC in rare cases, therefore, most of the communication that takes place is direct communication which accounts for more energy consumption as against OCER which forwards 1519 packets through intermediate nodes to the destination nodes at transmit power of −25 dBm. The multihop communication in OCER resulted in more packet forwarding.

For transmit powers of −15 dBm and −10 dBm, OCER shows the same trend as EPR and no packets go through the intermediate as the destination are in range due to high transmit powers.

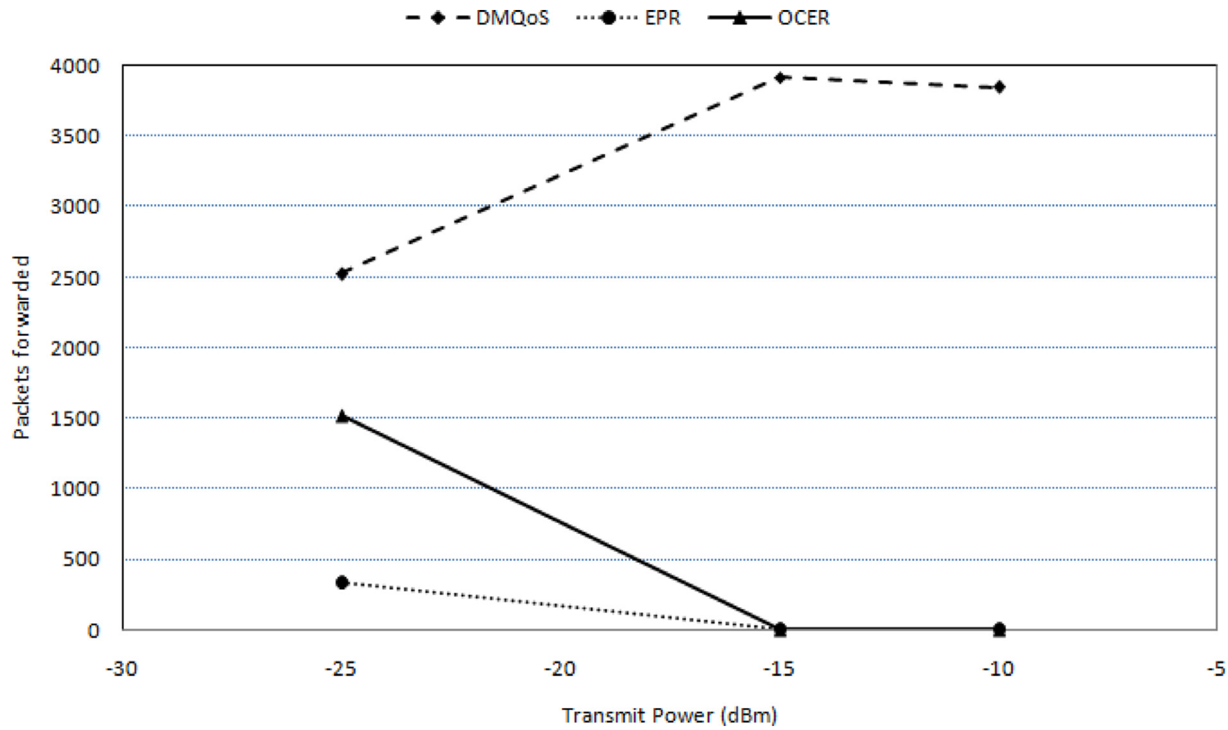


Fig. 5. Packets forwarded by intermediate nodes.

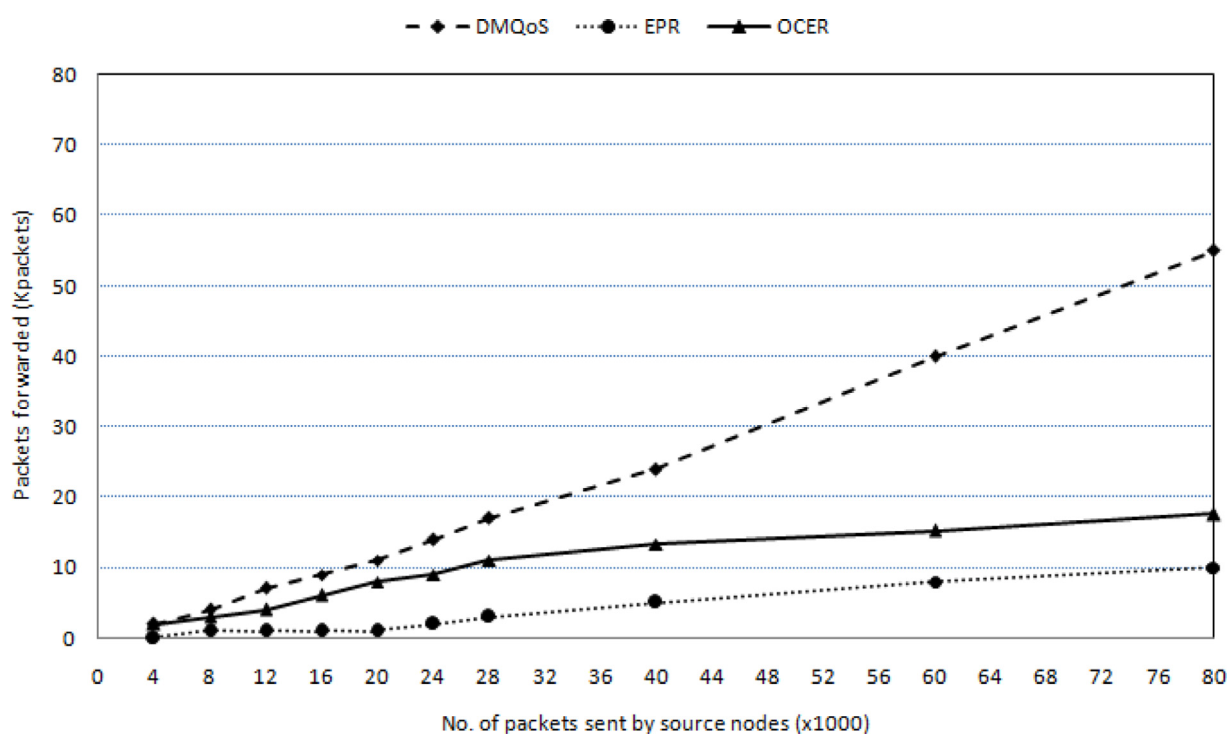


Fig. 6. Packets forwarded by intermediate nodes when transmit power is −25 dBm.

4.1.2. Scenario 2: variable number of packets are sent and all nodes are static

A total of 80,000 packets are sent by the BAN Coordinators (BC_1, BC_2, BC_3 and BC_4). The performance is evaluated after every 4000 packets until 28K are transmitted and thereafter when 40,000, 60,000, and 80,000 packets are sent by all BANCs. The parameters evaluated are successful transmission rate, number of packets forwarded by intermediate nodes and overall energy consumption.

Fig. 6 shows the number of data packets forwarded by intermediate nodes. In case of EPR, when the transmit power is −25 dBm and a total of 4-80K packets are sent from source nodes, 332-7843 packets are forwarded by the intermediate nodes as against 2.5-55.5K packets forwarded in DMQoS. Unlike DMQoS, EPR chooses the most appropriate next hop, but still most of the data is sent directly. In case of OCER, the number of packets forwarded by intermediate nodes are 2-17K, more than EPR but lesser than DMQoS. This increase in the number of forwarded packets is due to the

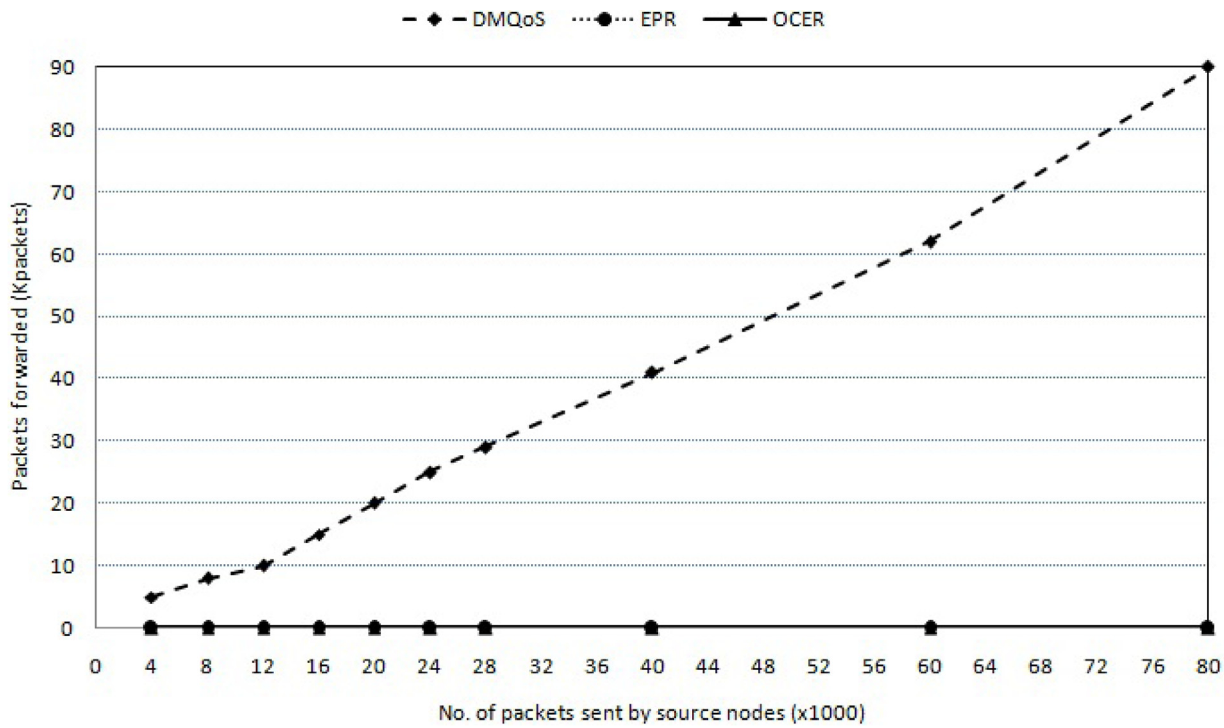


Fig. 7. Packets forwarded by intermediate nodes when transmit power is −15 dBm.

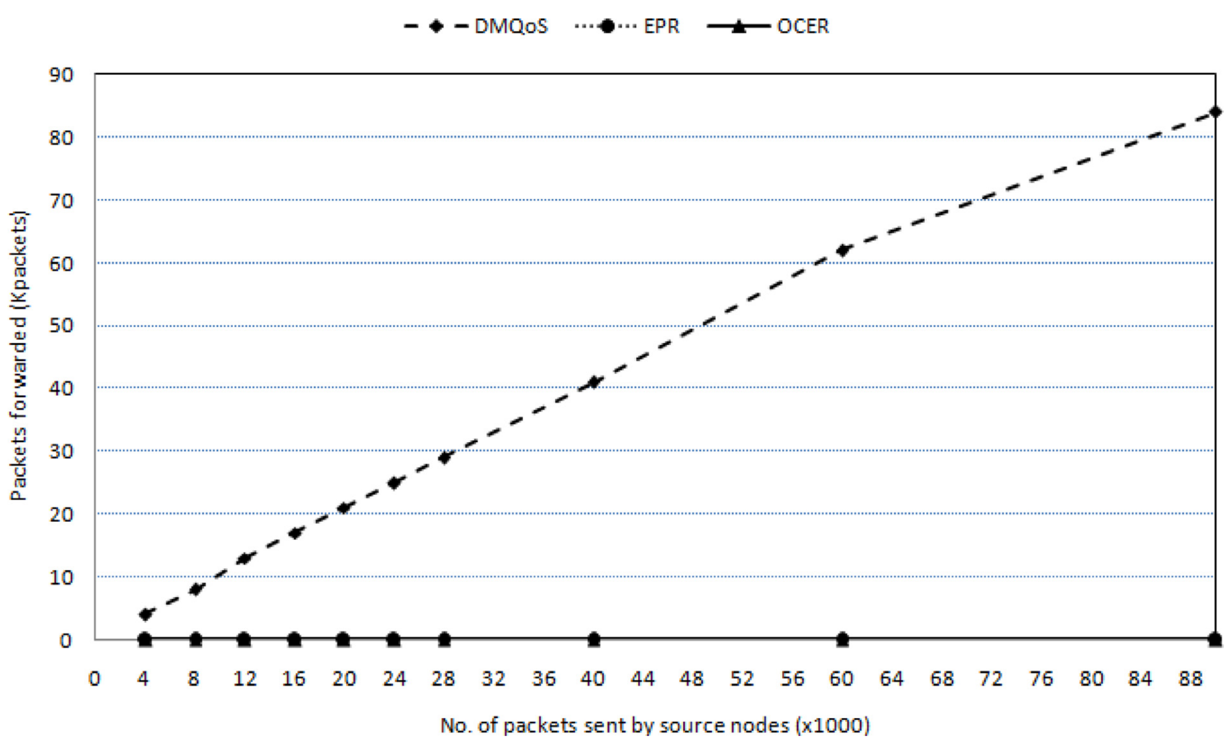


Fig. 8. Packets forwarding by intermediate nodes when transmit power is −10 dBm.

multi-hop communication and reliable link. Direct transmission of packets takes place whenever the transmit power is −15 dBm or above. Figs. 7 and 8 show that the number of packets forwarded by OCER and EPR is zero as compared to DMQoS in which intermediate nodes forward 4-87K packets.

From Fig. 9, it has been observed that for low transmit power of −25 dBm, EPR provides throughput from 67 to 76% and DMQoS provides throughput from 61 to 67% whereas OCER maintains its throughput from 90.8 to 92.5%. Throughput is increased as the probability of packet loss is reduced since the optimal data forwarder node is selected by utilizing a cost function which maintains the required reliability of the link.

As shown in Figs. 10 and 11, EPR achieves a throughput from 94 to 96% for both the transmit powers of −15 dBm and −10 dBm. The successful transmission rate of DMQoS is 83–88% and 82–88% for the transmit powers of −15 dBm and −10 dBm respec-

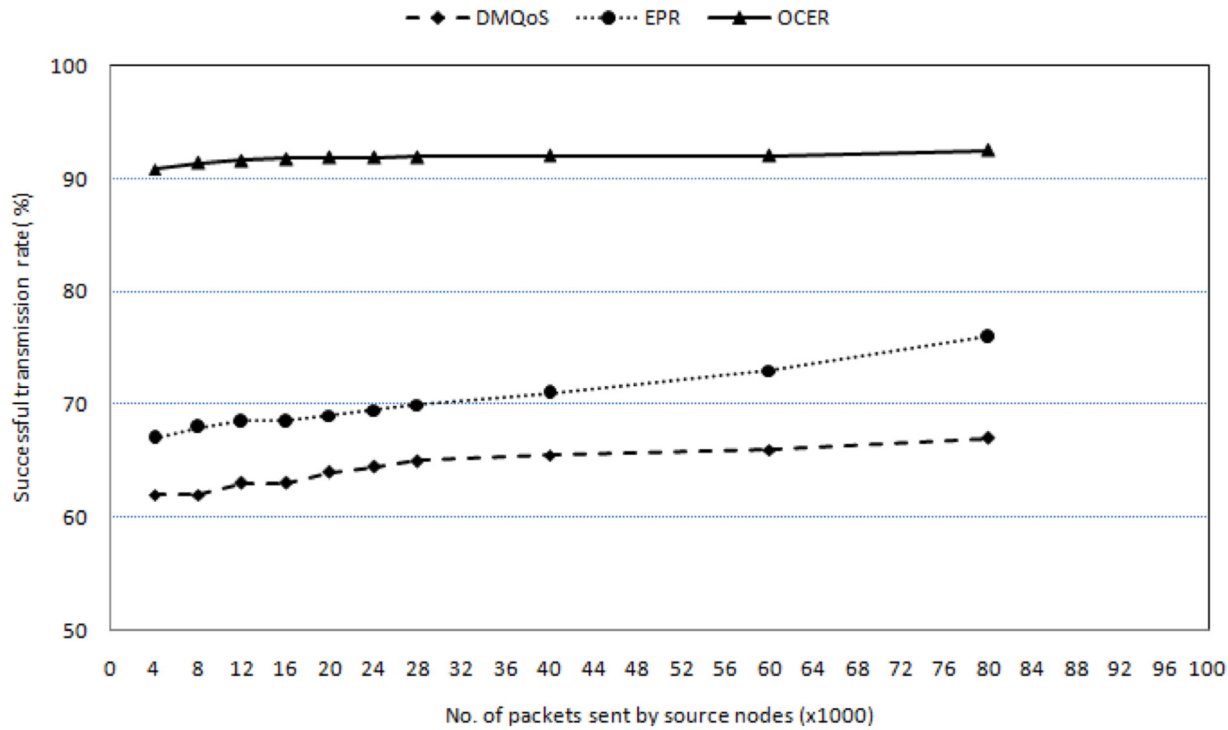


Fig. 9. Throughput when transmit power is −25 dBm.

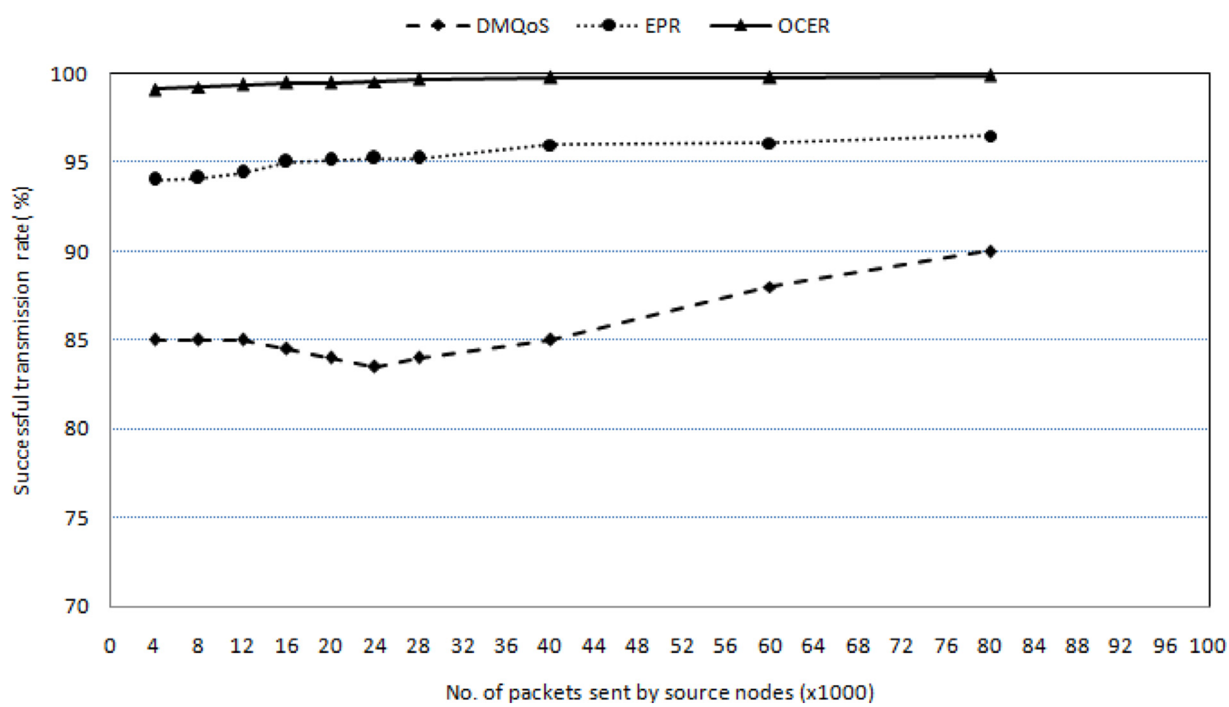


Fig. 10. Throughput when transmit power is −15 dBm.

tively. OCER provides consistently successful transmission rate of 99–99.9% for both transmit powers of −15 dBm and −10 dBm due to the reliable approach of selecting the next hop node.

4.1.3. Scenario 3: in this scenario, mobility of the source node BC_4 is taken into consideration. It is moving at a speed of 1 m/s vertically

The successful transmission rate and number of packets forwarded by intermediate nodes at the transmit power of −25 dBm are observed during the simulations of this scenario. The packets forwarding done by intermediate nodes is shown in Fig. 12. In case of EPR, 0-14K packets are forwarded by the intermediate nodes when 4-80K packets are transmitted from source nodes at the transmit power of −25 dBm as against 2-55K packets forwarded in DMQoS. Unlike DMQoS, EPR chooses the most appropriate next hop, but still most of the data is sent directly. In case of OCER, the number of packets forwarded by intermediate nodes are 5-25K which are more than EPR but lesser than DMQoS due to multi-hop communication and selection of the forwarder node by utilizing a cost function which takes care of the minimum required reliability whenever it has a packet to send. Fig. 13 shows that OCER has 83.8-94.7% successful transmission rate as compared to 70-82% of EPR and 63-66% of DMQoS.

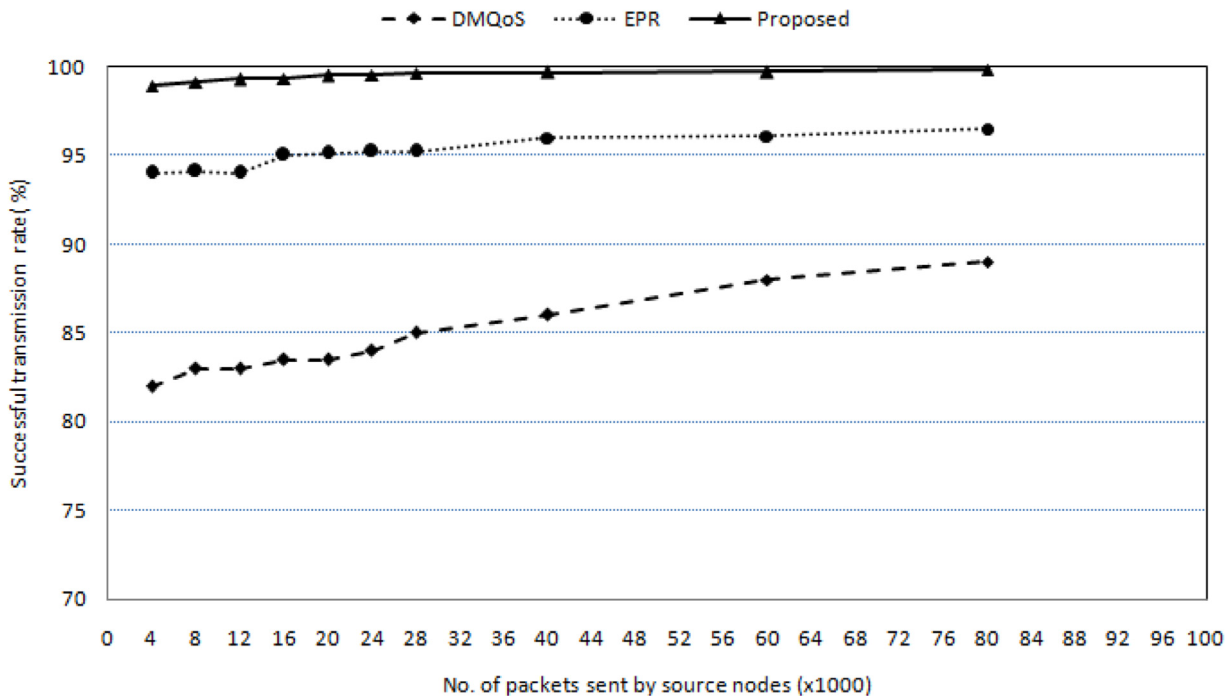


Fig. 11. Throughput when transmit power is −10 dBm.

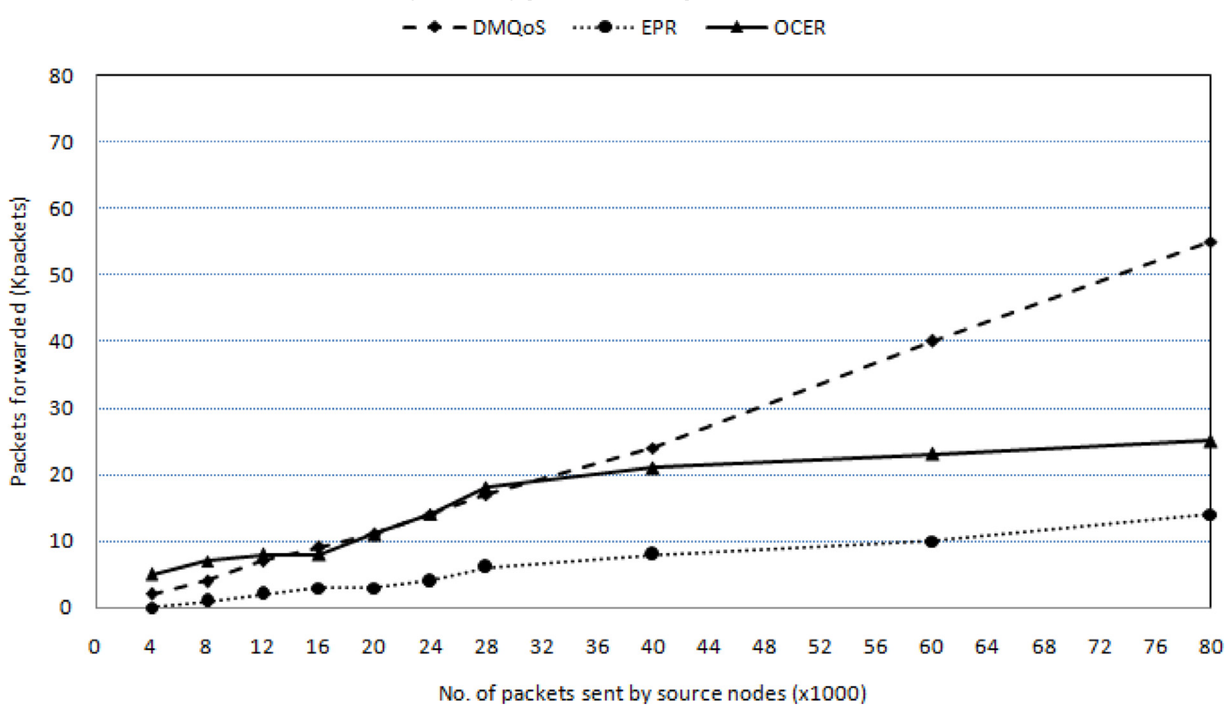


Fig. 12. Packets forwarded by intermediate nodes.

Table 7
Energy consumption comparison.

Transmit power(dBm)	E-OCER(mJ)	OCER(mJ)
−25	3668	6498
−15	4376	6512
−10	4634	6573

4.2. Comparison of E-OCER with OCER

The overall energy consumption of E-OCER and OCER in the network is shown in Table 7:

The results obtained for the same three scenarios are discussed below.

4.2.1. Scenario 1: fixed number of packets (1000 packets) are sent and all nodes are static

Fig. 14 shows that there is lesser energy consumption in case of E-OCER as compared to OCER for all the three transmit powers of −25 dBm, −15 dBm and −10 dBm. This is due to the large value of pathloss in human body. More is the pathloss, lesser is the radio transmission range for the same transmission power values. Due to decrease in transmission range, the source nodes can connect

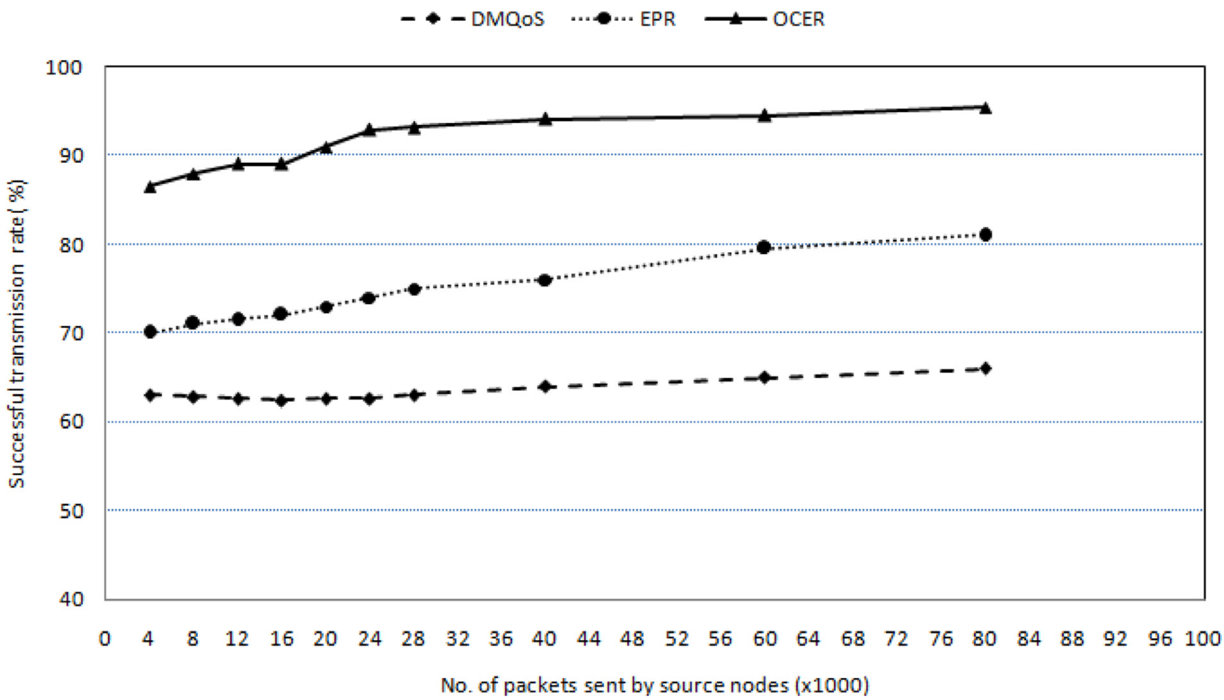


Fig. 13. Throughput.

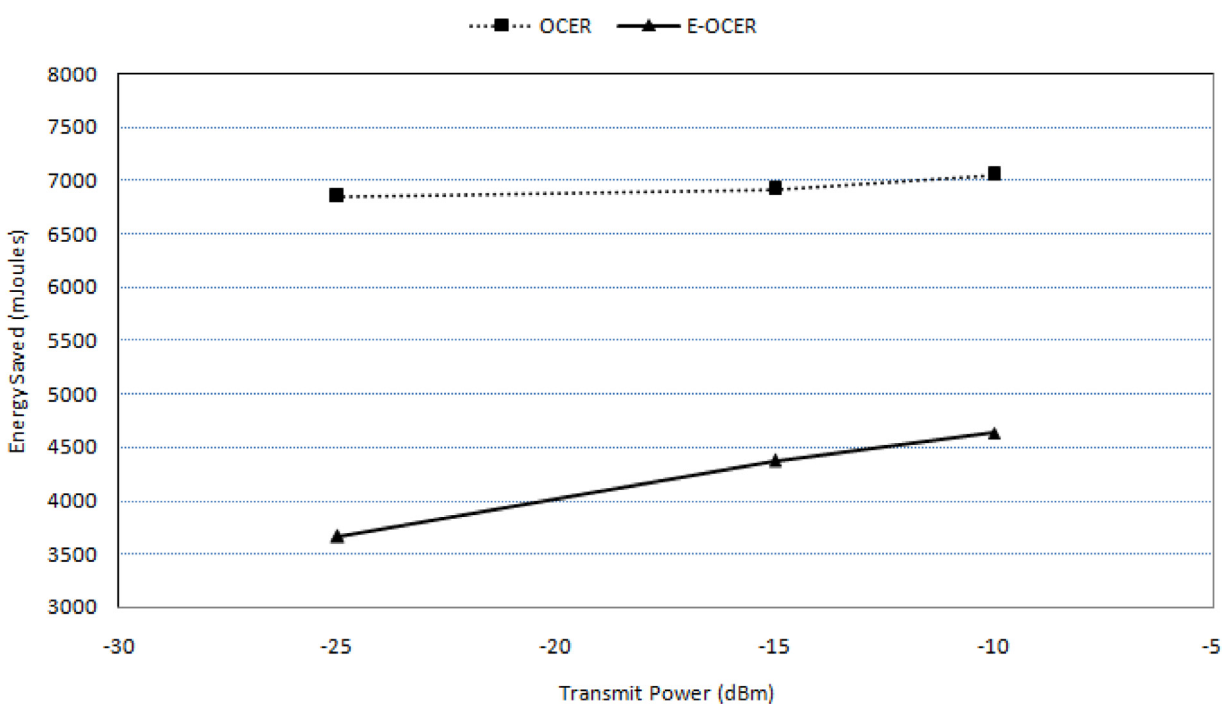


Fig. 14. Overall energy consumption.

to the sink node only with shorter links, using more number of hops. When the pathloss exponent decreases, the degree of multi-hopping increases exponentially which results in a decrease in the total energy dissipation. Using multi-hop communication links reduced the transmitter energy and hence average node energy decreases.

Fig. 15 shows the packet forwarded by the intermediate nodes. It has been observed that 1031 packets are forwarded by OCER at the transmit power of −25 dBm. For transmit powers of −15 dBm and −10 dBm, no packet goes through the intermediate nodes in OCER as the destinations are in range due to high transmit power. In case of E-OCER, since it involves communication within nodes placed on the human body, the source nodes can be connected to the destination node only with intermediate nodes due to increase in pathloss. This decreases the radio transmission range and the packets are transmitted through a reliable link, therefore number of packets forwarded are more as compared to OCER protocol. As the transmit power increases, the number of forwarded packets through intermediate nodes decreases. Fig. 15 shows that there are

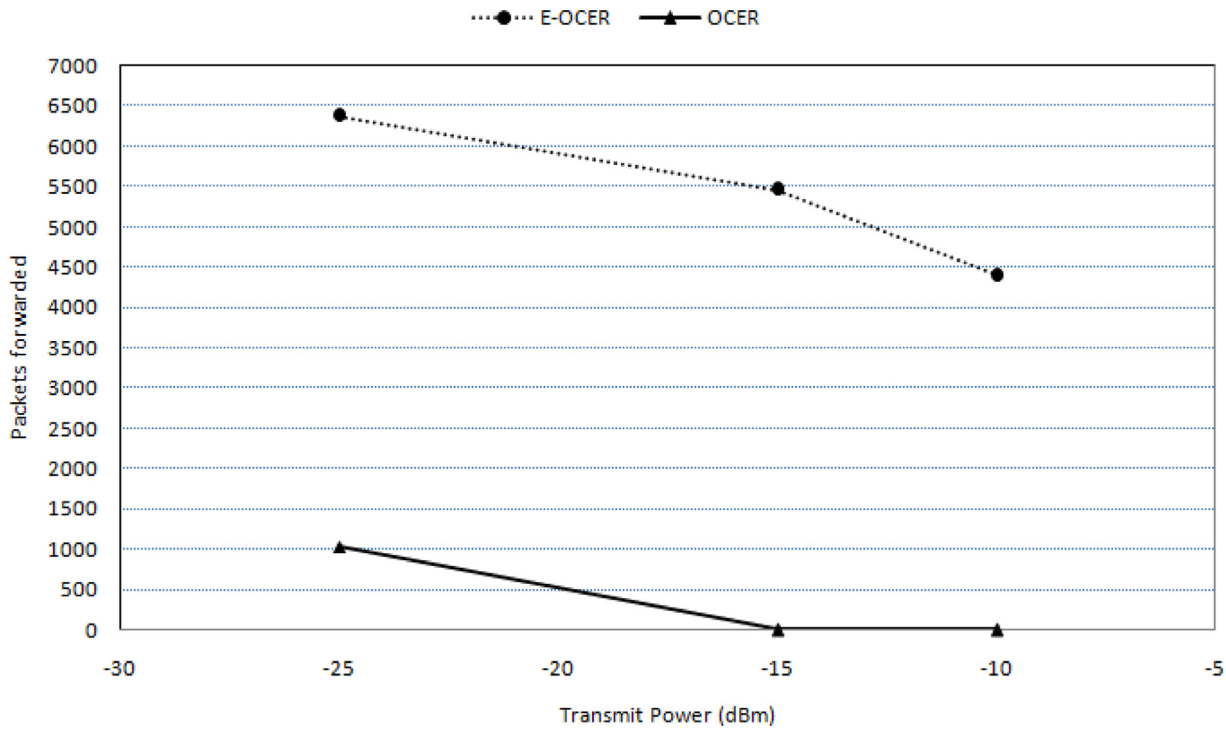


Fig. 15. Packets forwarded by intermediate nodes.

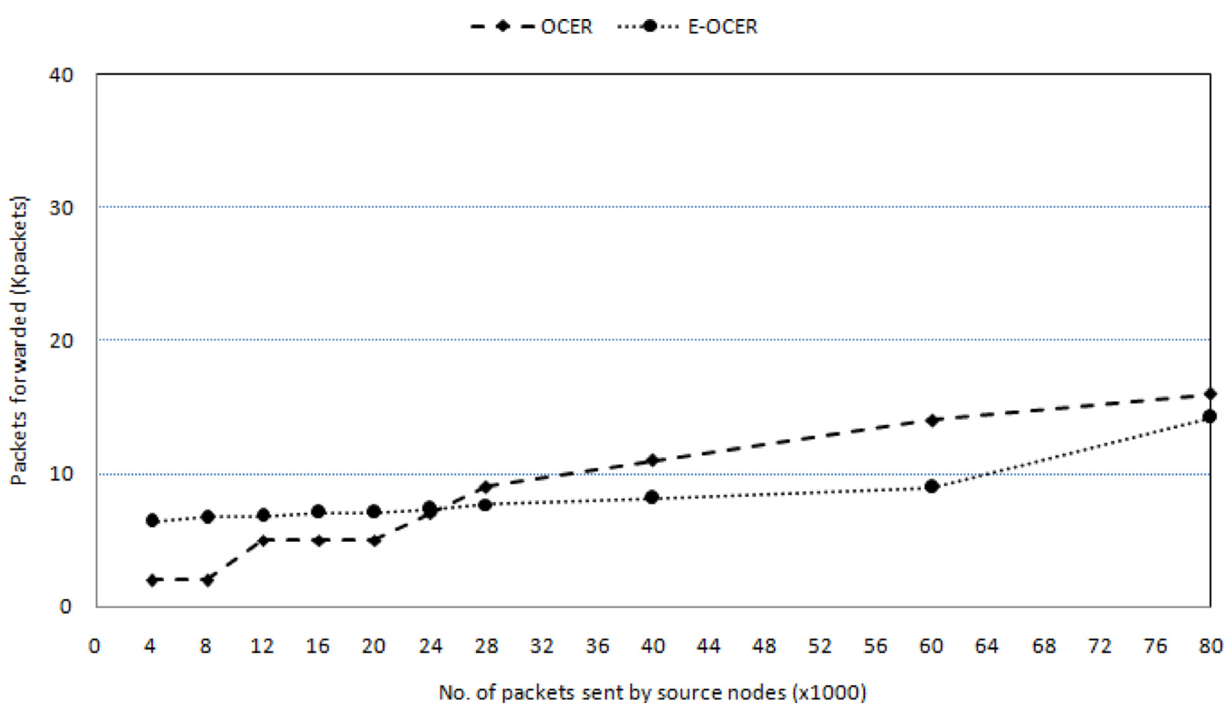


Fig. 16. Packet forwarded by intermediate nodes when transmit power is −25 dBm.

6377, 5465 and 4400 packets forwarded by intermediate nodes at transmit powers of −25 dBm, −15 dBm and −10 dBm respectively.

4.2.2. Scenario 2: variable number of packets are sent and all nodes are static

The source nodes transmit a total of 80,000 packets. The throughput and the packets forwarded by intermediate nodes are observed and recorded after every 4000 packets until 28K are transmitted and thereafter when 40K, 60K and 80K packets are sent by all BANs.

Fig. 16 shows the total packet forwarded by intermediate nodes. In the case of E-OCER, 2-16K packet forwarding is performed by intermediate nodes as against 6392-14,251 packets forwarded in OCER when 4-8K packets are transmitted from source nodes at the transmit power of −25 dBm. As the number of packets sent by intermediate nodes increases from 20-80K, the number of packets

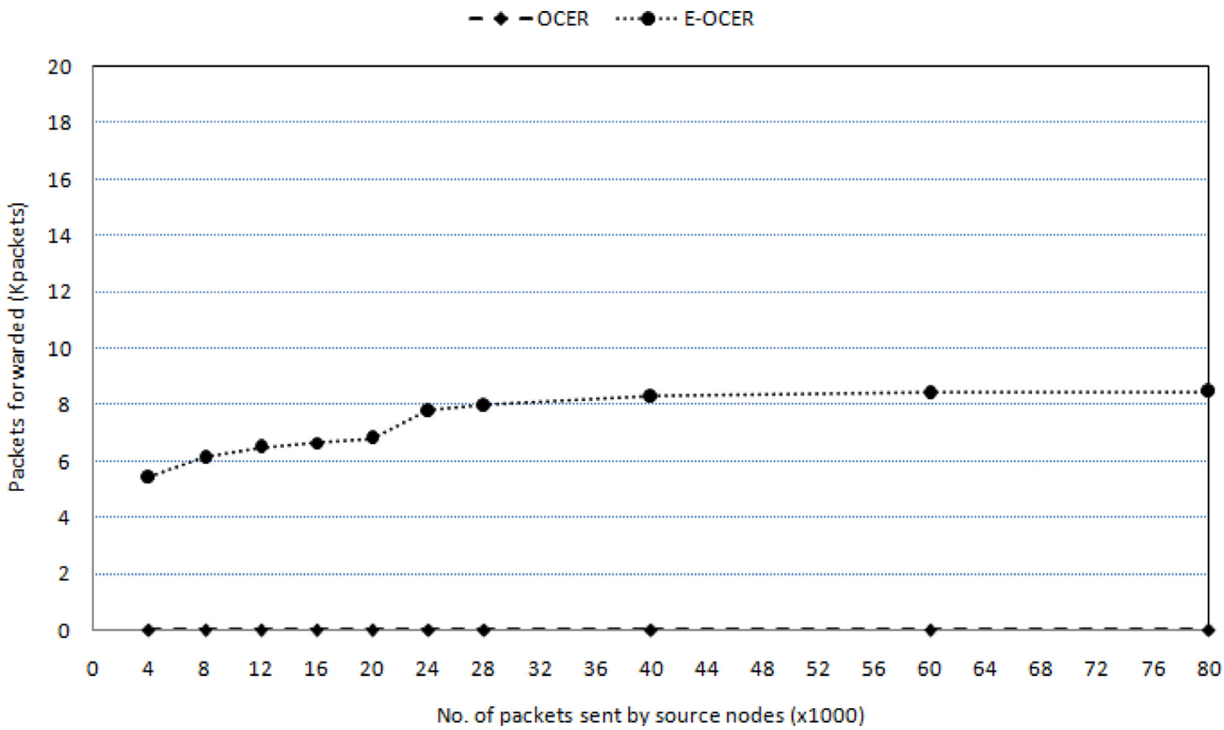


Fig. 17. Packets forwarded by intermediate nodes when transmit power is −15 dBm.

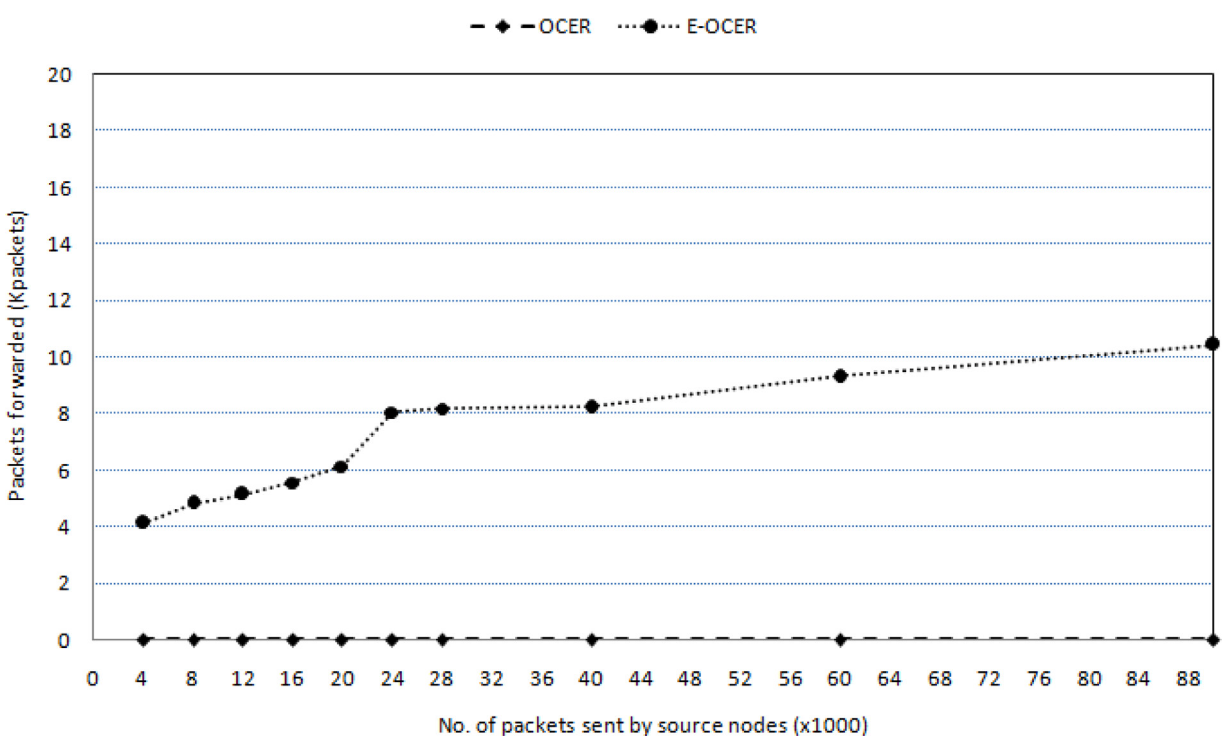


Fig. 18. Packets forwarded by intermediate nodes when transmit power is −10 dBm.

forwarded by intermediate nodes are less as compared to OCER. This is due to the fact that many nodes in the network means more hops available, therefore, many nodes near the shortest path participate in packet forwarding which can lead to congestion in the network.

Fig. 17 and Fig. 18 shows that in case of OCER, no packets are forwarded by intermediate nodes when the transmit power is −15 dBm and −10 dBm respectively. In case of E-OCER, intermediate nodes forward 5423-8475 packets for the same 4-80K packets transmitted by the source nodes when the transmit power is −15 dBm and 4112-10,441 packets when the transmit power is −10 dBm due to the communication of on-body nodes, where the radio transmission range is less, due to higher path loss; multi-hop communication takes place resulting in more number of packets forwarded.

We define throughput to be the total number of packets received at sink per round. As shown in Fig. 19, throughput of E-OCER is comparatively higher than OCER. OCER has a successful

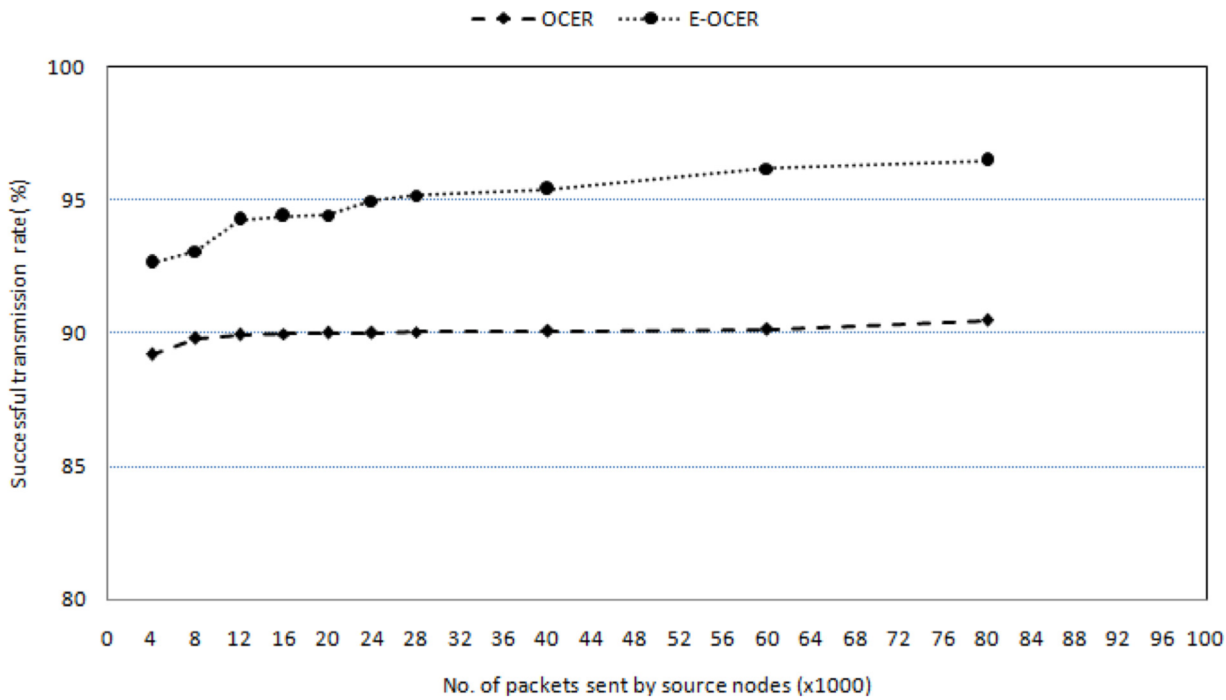


Fig. 19. Throughput when transmit power is −25 dBm.

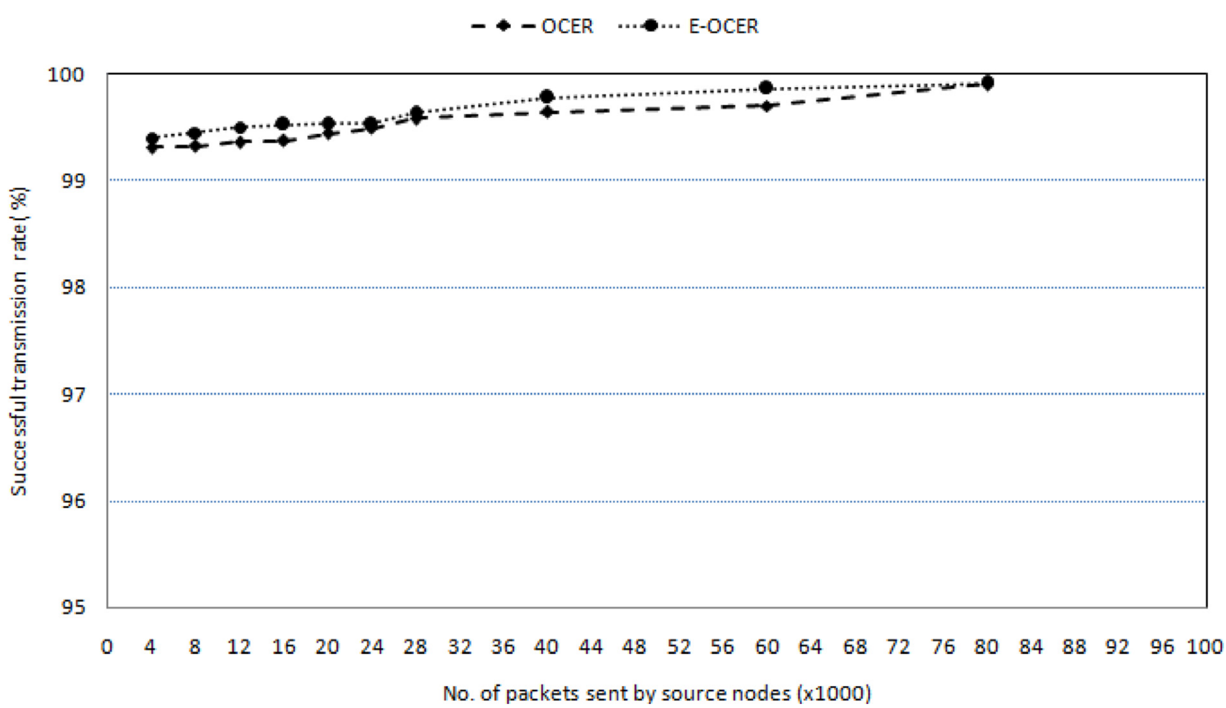


Fig. 20. Throughput when transmit power is −15 dBm.

transmission rate ranging from 89-0.5% for the transmit power of −25 dBm whereas the value for E-OCER lies between 93 and 96%.

As shown in Figs. 20 and 21, for the transmit power of −15 dBm and −10 dBm, the successful transmission rate of OCER lies between 99.3-99.9% and 99.2-99.7% respectively whereas in case of E-OCER, for transmit power of −15 dBm and −10 dBm, the successful transmission rate of OCER lies between 99 and 99.9%. Reliability has a direct impact on the throughput of the network. Since reliable links are established, high throughput is achieved. Moreover, the proposed protocols dissipates energy efficiently resulting in longer network lifetime. As the nodes are alive for a longer time, they send more packets which leads to increased throughput.

4.2.3. Scenario 3:variable number of packets are sent and the BANs are movable (this is to model patient mobility)

The packet forwarding performed by intermediate nodes and successful transmission rate at the transmit power of −25 dBm are observed during the simulations of this scenario. Fig. 22 shows the total packets forwarded by intermediate nodes. In case of OCER, 5-21K packets are forwarded by the intermediate nodes as against 7165-19,099 packets forwarded in E-OCER when 4-80K packets

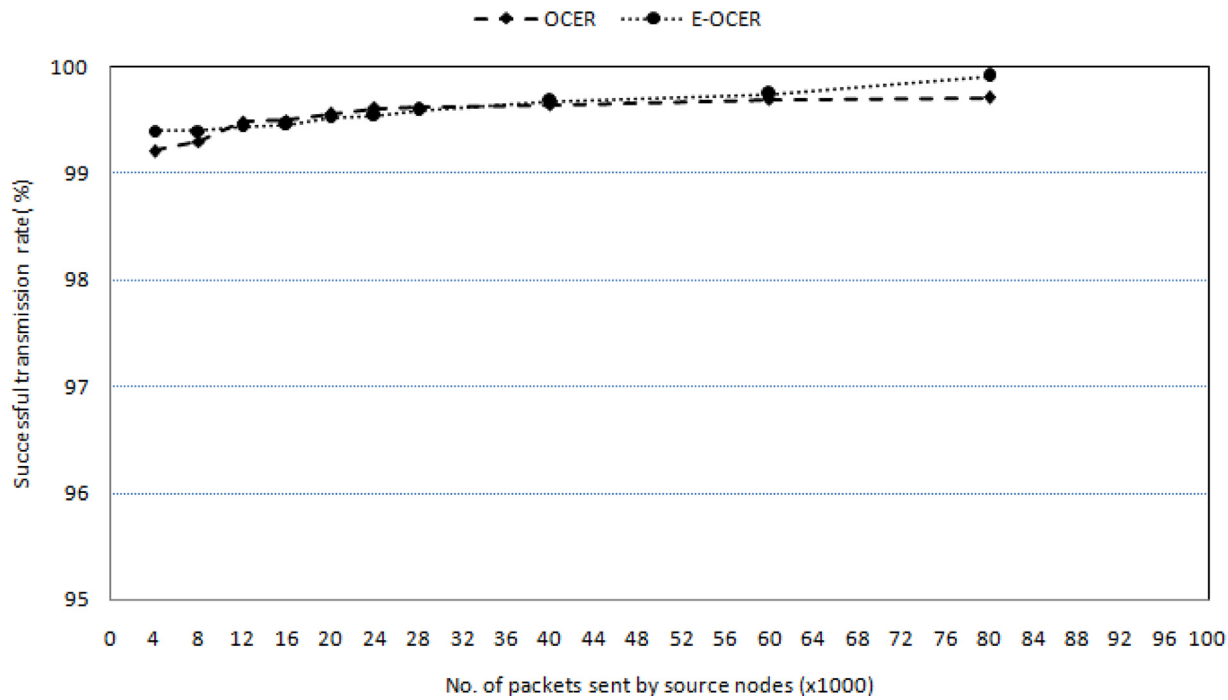


Fig. 21. Throughput when transmit power is −10 dBm.

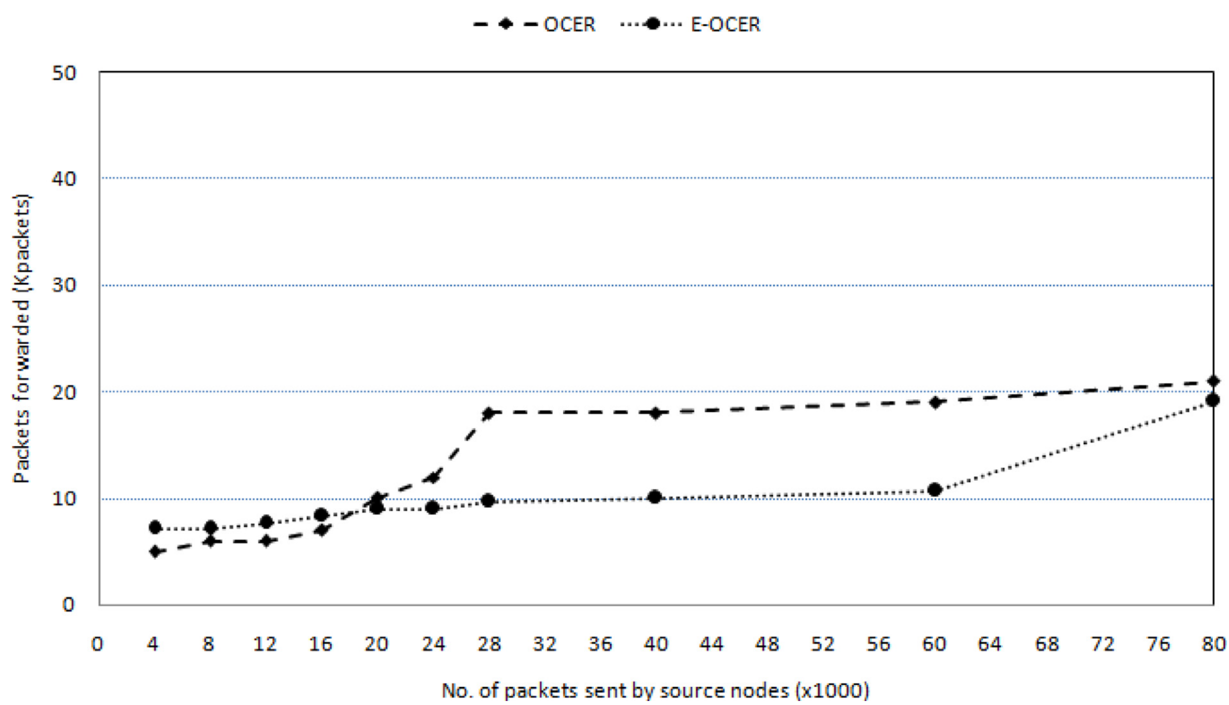


Fig. 22. Packets forwarded by intermediate nodes.

are sent from source nodes at the transmit power of −25 dBm. Packet transmission and hence the packet forwarding by intermediate nodes will depend on the location of mobile nodes. Fig. 23 shows that OCER has 83.7-94.7% successful transmission rate as compared to 84.46-94.2% of E-OCER. The low value of throughput is due to the mobility.

5. Conclusions and future work

This paper presents OCER and E-OCER - the energy efficient optimized reliable routing schemes for WBAN considering its continuous network operation so that WBAN sustains its functionality for the longest time. The proposed cost function is a function of node's residual energy, pathloss and link reliability. Node with minimum value of the cost function is selected as the forwarder node. Besides the energy consumption, pathloss model and reliability model, Genetic Algorithm based optimization for energy efficient routing is provided in this work. E-OCER extends OCER by considering inter-BAN communication using multihop approach. The protocol performance of OCER is compared with EPR and DMQoS in terms of energy consumption, throughput and total

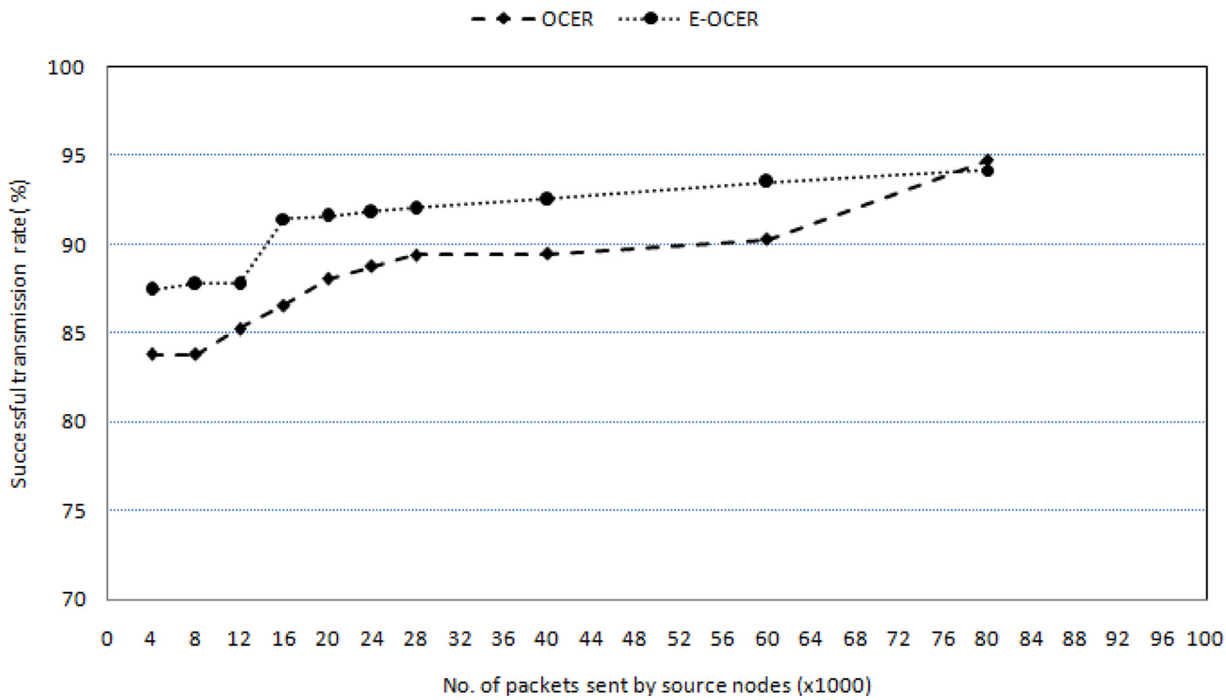


Fig. 23. Throughput when transmit power is −25 dBm.

packets forwarded by intermediate nodes. The numerical results illustrate that OCER could achieve upto 28-29% energy savings compared to EPR. Hence, the increased lifetime makes OCER invaluable for increasing the effectiveness of WBAN as a tool for patient care. The performance of E-OCER is compared with OCER which indicates lesser energy consumption of E-OCER as compared to OCER due to multi-hop communication. In the future work, the network model can be extended to consider more complex network scenarios in terms of accountability of various network topologies and cross layer interactions.

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