Body Node Coordinator Placement Algorithms for Wireless Body Area Networks

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***Abstract*—Wireless body area networks (WBANs) are intelligent wireless monitoring systems, consisting of wearable, and implantable computing devices on or in the human body. They are used to support a variety of personalized, advanced, and integrated applications in the field of medical, fitness, sports, military, and consumer electronics. In a WBAN, network longevity is a major challenge due to the limitation of the availability of energy supply in body nodes. Therefore, routing protocols can play a key role towards making such networks energy efficient. In this work, we exhibit that a routing protocol together with an effective body node coordinator (BNC) deployment strategy can influence the network lifetime eminently. Our initial work shows that the variation in the placement of a BNC within a WBAN could significantly vary the overall network lifetime. This motivated us to work on an effective node placement strategy for a BNC, within a WBAN; and thus we propose three different BNC placement algorithms considering different features of available energy efficient routing protocols in a WBAN. Our simulation results show that these algorithms along with an appropriate routing protocol can prolong the network lifetime by up to 47.45%.**

***Index Terms*—Body area network (BAN), body node coordinator (BNC) deployment, energy efficiency, human body, IEEE 802.15.6, Internet of Things (IoT), node deployment, wireless body area network (WBAN).**

I. Introduction

A WIRELESS body area network (WBAN) is formally defined by the IEEE 802.15 (Task group 6) as a communication standard optimized for low-power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics, personal entertainment, and others [1]. The primary concept of WBANs is to continuously monitor a patient's different biosignals such as electroencephalography (EEG), electrocardiography (ECG), blood pressure, sugar level, heart beat rate, body temperature by using sensor nodes, placed on different organs of a human body, and provide an efficient means of communication among these nodes with the outside world, i.e., a medical center. A WBAN connects these independent nodes by using a central controller, known as a body node coordinator (BNC). A BNC is primarily responsible for collecting information from nodes and sending them to the medical center [2]. Commonly, a mobile phone or a personal digital assistant (PDA) is used as a BNC to coordinate the functionalities of all nodes [3], [4]. The reason for using a BNC as coordinator of a WBAN, is to have limitation in transmission coverage, available energy and computational capability of used sensor nodes. Recent technological advances show that a sensor node, having a maximum transmit power of $-18.5\,\text{dBm}$ [5], can send its signal to another receiver node, having receiving sensitivity of $-92\,\text{dBm}$ [6], up to a distance of around 25 cm for on-body communication [7] without considering shadowing and fading effects. In case of in-body communication [8], for the same sensor node this distance is around 10.8 cm, without considering shadowing and fading effects, whereas the maximum dimension of a human body is about 171.4 cm [9]. This leads us to understand the lacking in transmission capability, within a WBAN as well as with the outside world, of commonly used sensor node. Again because of the energy constrained power supplies of tiny ($8.25\,\text{mm}^2$ [5]) sensor nodes, it is recommended to prolong their inactive time period utmost to enhance the entire network lifetime [10], which in turn proportionally lessens its possibility to be a coordinator of a WBAN. Consequently, all other aspects like quality of service (QoS), reliability, security, available energy supply, network longevity, and computational efficiency, lead us to a demand of self-contained coordinator where a BNC exhibits its precedence as coordinator compared to the tiny sensor node.

In WBANs, because of the energy constrained power supplies of tiny sensor nodes, effective energy consumption is a key challenge. Since about 80% of total energy is consumed only for communication purpose [11], a workable routing strategy can play a vital role to make the communication effective among nodes and prolong the lifetime of a WBAN. A routing strategy is a complete platform, which not only considers the routing protocol but also other aspects, e.g., effective node placement and relay node utilization, to make the overall system more energy efficient. In wireless sensor networks (WSNs), effective node placement, as an indispensable factor of routing strategy, which has drawn the attention of researchers extensively over the last decade. The aim of effective node placement is to prolong network lifetime. Present research [12] shows that it improves a network's energy efficiency by about 46%, which in turn prolongs the network lifetime. Effective node placement strategy is relatively new in WBANs. A WBAN consists of a number of sensor nodes and a BNC. Its sensor nodes are specific application oriented and these applications

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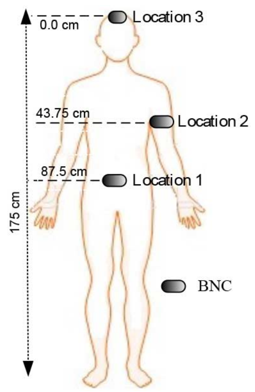

Fig. 1. Placements of a BNC on different parts of a human body.

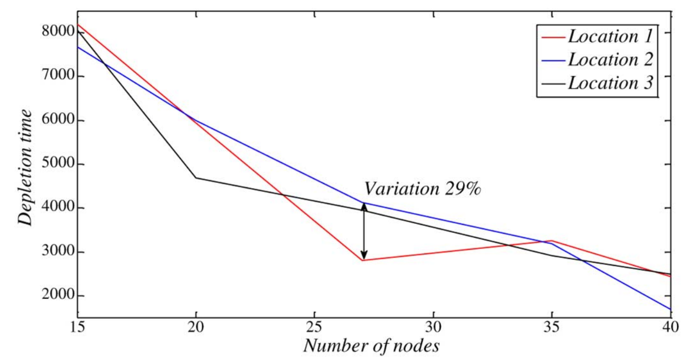

Fig. 2. Network lifetime with respect to the number of nodes, when nodes are uniformly distributed.

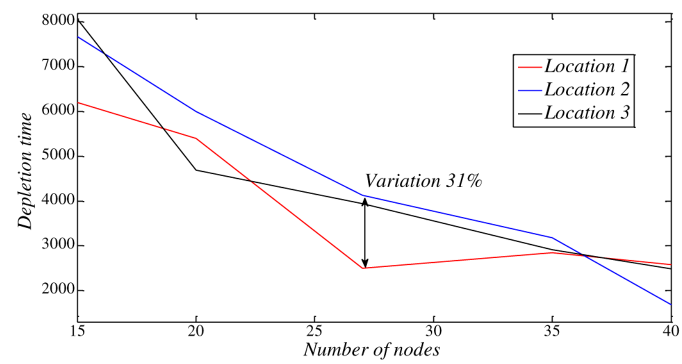

Fig. 3. Network lifetime with respect to the number of nodes, when nodes are nonuniformly distributed.

are strictly restricted by the sensor node's placement, on or in a human body, whereas a BNC has not such restricted placement issues. Thus, the BNC only exhibits the feasibility of effective placement in the WBAN. Considering its present demand and feasibility, here our research is on effective placement of a BNC within the WBAN, which can work along with existing routing protocols to enable the network to be more energy efficient. In our research, we have shown that effective BNC deployment along with routing protocol can affect network lifetime enormously and enhance the network lifetime by at most 47.45%.

This paper is organized as follows. Section II presents the problem definition, which explains the impact of our research towards our motivation. Section III illustrates the formation and working mechanism of our proposed algorithms. Section IV presents the system model, based on which the performance of proposed algorithms, together with routing protocols, was evaluated. Comparative performance evaluation is shown in Section IV. Finally, Section V ends with the conclusion and our future works.

II. Problem Statement

In our previous research [13], we have found that the placement of a BNC eminently influences the longevity of the entire WBAN. To understand its impact, we used the same system model of [13] to simulate the routing protocol known as energy efficient adaptive routing in wireless body area network (EAR-BAN) [13]. Here, we have considered both uniform and nonuniform distribution scenarios of nodes of a WBAN; and a BNC was placed in one of three different locations of a human body for each scenario, as depicted in Fig. 1. For the BNC placement on the human body, our considered locations were waist (Location 1), upper limb (Location 2), and head (Location 3). These locations are commonly used and mostly feasible for the BNC placement [4], [7]. Since these are nearly equally spaced, thus these also give an approximate analysis of network longevity due to the varying position of the BNC. Waist seems to be the center part of a human body. Sometimes wrist is also used to place a BNC instead of the waist. But, due to the regular postural change of wrist, we prefer waist instead of the wrist. Again, head and lower leg are two possible end parts of a human body to place a BNC; but, in our research, we considered head instead of lower leg, because of frequent postural change of human legs. Since we have already considered the center part and the end part of a human body, as two possible locations for a BNC placement; thus, we have considered a third location between these two locations to understand the impact of energy consumption due to the placement of a BNC. We considered upper limb as "Location 2," which is a middle part between waist and head. The results, shown in Figs. 2 and 3, are for uniformly and nonuniformly distributed nodes, respectively. Here, we consider only one BNC placed in one of three locations at each time to measure network longevity. Such as for "Location 1" of Fig. 2, a BNC was placed on waist (Location 1) and nodes were uniformly distributed. These results, based on three specific scenarios of three different placements of a BNC, are revealing the fact that the network lifetime of a WBAN varies with its BNC's placement and it is random. Simulation results show that these varying positions of a BNC vary the network lifetime at most 29%, for uniformly distributed nodes compared to the worst case scenario, whereas for nonuniformly distributed nodes, it is at most 31% compared to the same worst-case scenario. Here, the simulation results of both Figs. 2 and 3 show that the network longevity is the lowest one when the BNC is placed at waist (Location 1). Thus, it is considered as the worst-case scenario among three considered scenarios (Locations 1–3). At the end, these outcomes help us to realize the importance of effective location estimation for a BNC within a WBAN to maximize the network longevity.

III. Proposed Algorithms

In Section I, it was stated that effective node placement in a WBAN is defined as a means of effective BNC placement rather than a sensor node deployment. Although a sink node placement in WSNs is similar to a BNC placement in WBANs, the commonly used node placement techniques of WSNs are not unerringly feasible for WBANs. From every aspect, e.g., path loss model, energy consumption model, scale, hardware architecture, computational complexity, a WBAN differs from a WSN [7], [11]. This leads us to understand that the placement strategy of a BNC of WBANs is incompatible with the sink node placement of WSNs. Commonly, effective node placement strategy of WBANs should have the following requirements:

1) less computational complexity and message exchange complexity;
2) centralized operation;
3) less involvedness of sensor nodes to enable the network energy efficient.

The aforementioned factors motivated us to work on a new-minted node placement algorithm other than the conventional ones, used in WSNs. In WSNs, genetic algorithm [14], particle swarm optimization algorithm [15], artificial potential field-based algorithm [16], and computational geometry-based algorithm [17] are the widely used four different node placement techniques [18]. The primary drawback of using these conventional techniques is that they experience an extensive computational burden. Genetic algorithms have time complexity of $O\left(nL + n^2 + \sum_{i=1}^{k} n_i^3\right)$ [14] where L is the number of random samples for evaluation or received message, $n = \sum_{i=1}^{k} n_i$, where $i = 1, 2, \ldots, K$ and K is the number of sensor nodes. Particle swarm optimization algorithm is applicable for networks where nodes are mobile whereas, in WBANs, nodes are mostly static. It also requires superior computational support, than others. Artificial potential field-based algorithm is also a real time obstacle avoidance approach for mobile nodes [16]. According to the computational geometry-based algorithm, each node should have precious location information of itself as well as others of a network, which is also not feasible for a WBAN because each node has limited transmission coverage and unambiguous location estimation is still under development.

All of these conventional techniques require great computational support at the coordinator, i.e., the BNC. Bulky computation means huge data processing, by a BNC. These data are received by existing nodes of the network. This increases the radio communication between a BNC and nodes, which in turn increases the amount of energy consumptions of nodes. Therefore, increasing complexity also increases the energy computation of a network and decreases its lifetime expectancy.

Since the nodes of a WBAN are highly energy constraint and mostly nonrenewable, therefore, considering the feasibility of WBANs, we have proposed novel algorithms which are less computational complex. In this section, at first we have proposed our metric, based on which, we have illustrated the working principle of our proposed algorithms.

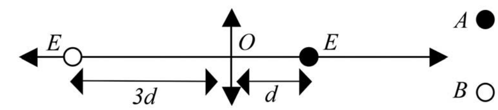

Fig. 4. Scenario 1.

A. Metric Selection

Here, our focus is on network longevity, thus, we have to consider a metric that can estimate the actual scenario of lifetime expectancy of nodes of a WBAN. Commonly, we use either distance or available energy-based metric of a node to account its lifetime, where distance is used as a means of path loss and available energy of a node indicates its present residual energy. But, individually, none of these are adequate enough to present the actual lifetime expectancy of a node. To support our argument, we have considered two different scenarios as illustrated below.

In scenario 1, shown in Fig. 4, nodes A and B have the same available energy E but they are placed at a distance d and $3d$, respectively, with respect to the center location O. Now, from [19], we know a radio spends energy during transmission ($E_{Tx}(\mathrm{nJ})$), in order to process k number of bits over a distance D with path loss coefficient η; i.e.,

$$E_{Tx}(k, d, \eta) = E_{Tx\_\mathrm{elec}} * k + E_{\mathrm{amp}}(\eta) * k * D^{\eta}. \quad (1)$$

Here, $E_{Tx-\mathrm{lec}}(\mathrm{nJ/bit})$ is the energy dissipated by the radio to run the circuitry of the transmitter and $E_{\mathrm{amp}}(\eta)(\mathrm{J/(bit.m^{\eta})})$ is the energy dissipated by the transmit amplifier. Now except transmission distance (D), if other parameters are constant then (1) becomes

$$E_{Tx} \propto D^{\eta}. \quad (2)$$

Equation (2) leads us to

$$\begin{aligned} &\text{when } D^{\eta}(\text{node } A) < D^{\eta}(\text{node } B) \\ &\text{then } E_{Tx}(\text{node } A) < E_{Tx}(\text{node } B), \qquad \text{for } \eta \geq 0. \end{aligned}$$

Now, for a node with a fixed initial energy (E), after a certain time period later, its energy will be ($E - E_{Tx}$). Since nodes A and B have different transmission distance (D), their longevities will be different; i.e., lifetime of node A is greater than lifetime of node B. Here, although nodes A and B have the same initial available energy (E), but because of different transmission distance their longevities are different. This explanation leads us to understand that only the available energy of a node cannot be used as a measurement of its lifetime expectancy.

Again, in scenario 2, shown in Fig. 5, nodes A and B are placed at a fixed distance d with respect to the center location O, and their initial available energies are E and $3E$, respectively.

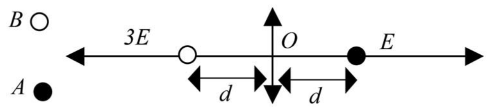

Fig. 5. Scenario 2.

TABLE I
LIFETIME EXPECTANCY OF NODES A AND B

Lifetime of node A	Lifetime of node B
E–E_{Tx}	$3E$–E_{Tx}

Equation (2) results in

$$\begin{aligned} &\text{when } D^{\eta}(\text{node } A) = D^{\eta}(\text{node } B) \\ &\text{then } E_{Tx}(\text{node } A) = E_{Tx}(\text{node } B), \qquad \text{for } \eta \geq 0. \end{aligned}$$

Since the initial available energies of nodes A and B are different, thus after a certain time period their available energies will also be different which is shown in Table I.

Therefore, although nodes A and B have a fixed transmission distance (D), but their different levels of initial available energies result in different levels of longevities; i.e., lifetime of node $A <$ lifetime of node B. This elucidation also helps us to understand that only the transmission distance of a node cannot measure its lifetime expectancy precisely.

The above analysis illustrates that neither available energy nor the transmission distance could show the network lifetime, or more specifically a node's lifetime, properly. Therefore, we propose a new metric $\frac{E_{\text{av}}}{\text{PL}}$ which indicates a node's lifetime, in seconds. Here, E_{av} is the available energy of the node and PL is the path loss between the node and the BNC. Again path loss PL is proportional to the transmission distance d, which will be explained in Section IV. Thus, we propose $\frac{E_{\text{av}}}{d^{\eta}}$ to estimate the lifetime expectancy of a node. Based on this metric we propose three different algorithms, for effective placement of a BNC within a WBAN to prolong the entire network lifetime. Since these BNC placement algorithms are going to work along with the routing protocols of WBANs, based on the features of available energy efficient routing protocols, we categorize them into three different streams. For each stream, we propose a BNC placement algorithm. They are:

1) distance-aware BNC placement algorithm-iterative (DBP-I);
2) distance-aware BNC placement algorithm-fixed (DBP-F);
3) Position-aware BNC placement algorithm (PBP).

Here, PBP is applicable for those routing protocols in which the sensor nodes of a WBAN know their spatial locations. Whereas for DBP-I and DBP-F, the requirement is that the sensor nodes, instead of knowing their coordinate, should know the relative distance from the center coordinator, i.e., a BNC. Again there are some routing protocols in WBANs, which consider one of its available sensor nodes as a center coordinator instead of considering a separate computationally efficient BNC. Since the sensor nodes are less computationally efficient, this type of routing protocol requires less complex BNC placement technique. DBP-F is thus applicable for them. Besides, the routing protocols, which consider the existence of a BNC as a center coordinator, DBP-I is applicable for them. These algorithms are different in their basic infusion, principle and formation complexity, leading to the computational complexity, which results in different graded energy efficient performance. These algorithms are explained as follows:

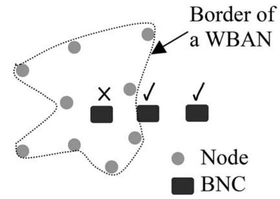

Fig. 6. Initial BNC placement scenario.

B. Distance-Aware BNC Placement Algorithm-Iterative

Our proposed *DBP-I* is used to find out the effective location of a BNC within a WBAN to enable the system more energy efficient. It is applicable for those routing protocols in which the BNC knows the relative communication distance of nodes. In WBANs, there is a number of routing protocols, such as energy efficient adaptive routing in EAR-BAN [13], semiautonomous adaptive routing in wireless body area networks (SEA-BAN) [19], and probabilistic energy-aware routing protocol (PER) [20], which support its requirements.

1) Considerations:

a) Initially, the BNC should be placed at the border or outside of the border of a WBAN.
b) All nodes of a WBAN should be within the transmission coverage of the BNC.
c) The BNC should know the relative transmission distances of all nodes from itself.

2) Working Mechanism: The execution of *DBP-I* is started with the placement of the BNC. According to *DBP-I*, the BNC should be placed at the boundary or outside of the boundary of a WBAN as depicted in Fig. 6 [step 1]. A common practice is to choose the location of one of the farthest nodes, in any direction, with respect to the center of the WBAN and place the BNC at that location. At first, the BNC measures the relative communication distances of all nodes of the WBAN [step 2] and based on the measured distances finds out $d_{\min}$ and $d_{\max}$, the distances of closest and farthest nodes, respectively [step 3a]. Then the BNC estimates D_{avg}, which is an intermediate distance between $d_{\min}$ and $d_{\max}$, and divides all available nodes into two subsets (U_L and U_R), considering D_{avg} as a threshold [step 3b]. After that, the BNC has to be shifted D_{avg} distance away towards the center of the WBAN [step 3c] and once again it measures the relative communication distances of all nodes from its new location [step 3d]. Now, for each node, it accounts a node's utility factor (UF), based on the available energy and relative communication distance (d_{r_j}) of a node, from itself [step 3e]. Then, it sums up the node's UF (sum_{UL} and sum_{UR}) for each subset (U_L and U_R) [step 3f]. Finally, it considers the following criteria to repeat the entire process [step 3g].

Here, if $\frac{\text{sum}_{U_L}}{\text{number of node in } U_L(\#U_L)} \geq \frac{\text{sum}_{U_R}}{\text{number of node in } U_R(\#U_R)}$ and $\#U_L > 1$, then the BNC considers the subset U_L and repeats the entire process.

Again, if $\frac{\text{sum}_{U_L}}{\text{number of node in } U_L} < \frac{\text{sum}_{U_R}}{\text{number of node in } U_R}$ and $\#U_R > 1$, then the BNC repeats the entire process considering the subset U_R.

On the contrary, if in the selected subset (U_L or U_R), there exists only one node, then the present location is seemed to be the optimal location of the BNC.

3) Algorithm: DBP-I:

Algorithm: DBP-I

1. *Place the BNC at any end point of a WBAN, say the point is P*
2. *Measure the relative distance of all body nodes (N_1, $N_2, \ldots, N_j$) from the BNC. Here, $\forall N\colon N_j \in U_j$*
3. *if $\#U_j > 1$ then*
    - a. *Find the distant node and closest node of U_j . Let, the distances are d_{max} and d_{min} respectively.*
    - b. *Estimate $D_{avg} = \frac{d_{max} + d_{min}}{2}$; and split U_j into two subsets of U_L and U_R.*
      $\forall N\colon N_L \in U_L$; *where for node N_L, distance $(N_L) \geq D_{avg}$*
      $\forall N\colon N_R \in U_R$; *where for node N_R, distance $(N_R) < D_{avg}$*
    - c. *Replace the BNC, D_{avg} distance away from point P towards the center of the WBAN*
    - d. *Measure the relative distance $(d_{r_1}, d_{r_2}, \ldots, d_{r_j})$ of all body nodes from BNC's new position*
    - e. $\forall N\colon N_j \in U_j$ *Utility Factor,*
      $UF(N_j) = \frac{available\ energy\ of\ node\ N_j}{(d_{r_j})^{\eta}}$
    - f. $\forall N\colon N_L \in U_L\ Sum_{U_L} = \sum_{N_L \in U_L} UF(N_L)$
      $\forall N\colon N_R \in U_R\ Sum_{U_R} = \sum_{N_R \in U_R} UF(N_R)$
    - g. $d_{min} \leftarrow D_{avg}$ *and* $U_j \leftarrow U_L$ *if* $\frac{Sum_{U_L}}{\#U_L} \geq \frac{Sum_{U_R}}{\#U_R}$
      $d_{max} \leftarrow D_{avg}$ *and* $U_j \leftarrow U_R$ *if* $\frac{Sum_{U_L}}{\#U_L} < \frac{Sum_{U_R}}{\#U_R}$
    - h. *repeat step-3*
      else set the BNC at that position.

C. Distance-Aware BNC Placement Algorithm-Fixed

Like *DBP-I*, *DBP-F* is also applicable for effective location selection of BNC, within a WBAN, to prolong its network lifetime. It is proposed based on the similar requirements of *DBP-I*. The primary difference, in formation, between *DBP-I* and *DBP-F* is the computational complexity. *DBP-F* exhibits linear computational complexity, whereas *DBP-I* supports iterative computation.

1) Considerations:

a) Initially, the BNC should be placed at the border or outside of the border of a WBAN.

b) All nodes of a WBAN should be within the transmission coverage of the BNC.

c) The BNC should know the relative transmission distances of all nodes from itself.

2) Working Mechanism: Like *DBP-I*, operation of *DBP-F* is begun with the placement of the BNC. Its successive work functionalities are stated as follows.

Step 1) A BNC should be placed at least at the boundary or outside of the boundary of a WBAN as depicted in Fig. 6. A common practice is to choose the location of one of the farthest nodes, in any specific direction, with respect to the center of a WBAN and places the BNC at that location.

Step 2) BNC measures the relative communication distances of all available nodes of the WBAN.

Step 3) Based on the measured distances of step 2), the BNC finds out $d_{\min}$ and $d_{\max}$, the distances of closest and the farthest nodes respectively.

Step 4) BNC estimates D_{avg}, which is a median distance between $d_{\min}$ and $d_{\max}$; and divides all available nodes into two subsets (U_L and U_R) based on their relative communication distances from the BNC, considering D_{avg} as a threshold.

Step 5) BNC has to be shifted D_{avg} distance away towards the center of the WBAN.

Step 6) Again it measures the relative communication distances $(d_{r_1}, d_{r_2}, \ldots, d_{r_j})$ of all nodes (N_1, $N_2, \ldots, N_j$)) from its new location.

Step 7) BNC sums up the available energy (E) and relative communication distance (d_r) of all nodes of each subset (U_L and U_R) and divides each of the outcomes with the number of available node of its associated subset.

Step 8) BNC estimates the correlation (X), of measured UFs of two subsets, leading to the distance discrimination (d). Here, the term "distance discrimination" is used to find out proper location estimation of optimal location of the BNC, within a WBAN.

Step 9) Finally, the BNC is placed its optimal location. Here, the term k is a user-defined constant, which is used as a tolerance limit of estimated value. In our work, we have considered $k = 0.5$. It is found that for the range [0,1], $k = 0.5$ results the optimum value to find out the optimal position of the BNC to prolong network lifetime.

3) Algorithm: DBP-F:

Algorithm: DBP-F

1. Place a BNC at any end point of a WBAN. Say it is $P(X, Y)$
2. Measure the relative distance of all body nodes $(N_1, N_2, \ldots, N_j)$ from the BNC. Here, $\forall N\colon N_j \in U_j$
3. Find the distant node and closest node of U_j. Let, the distances are d_{max} and d_{min}, respectively.
4. Estimate $D_{avg} = \frac{d_{max} + d_{min}}{2}$; and split U_j into two subsets of U_L and U_R.
   $\forall N\colon N_L \in U_L$; where for node N_L, distance $(N_L) \geq D_{avg}$
   $\forall N\colon N_R \in U_R$; where for node N_R, distance $(N_R) < D_{avg}$
5. Replace the BNC, D_{avg} distance away from point P towards the center of the WBAN. Say it is $(X - D_{avg}, Y) \equiv (X, Y)$
6. Measure the relative distance $(d_{r_1}, d_{r_2}, \ldots, d_{r_j})$ of all body nodes $(N_1, N_2, \ldots, N_j)$ from the BNC's new position

7. $\forall N\colon N_L \in U_L \;\; E_L = \frac{\sum_{N_L \in U_L} E_{N_L}}{\#U_L} \;\; d_L^{\eta} = \frac{\sum_{N_L \in U_L} {d^{\eta}}_{r_L}}{\#U_L}$; d_{r_L} is the corresponding distance of node N_L from BNC
   $\forall N\colon N_R \in U_R \quad E_R = \frac{\sum_{N_R \in U_R} E_{N_R}}{\#U_R}$
   $d_R^{\eta} = \frac{\sum_{N_R \in U_R} {d^{\eta}}_{r_R}}{\#U_R}$; *$\eta$ is the path loss exponent*
8. $EstimateX = \frac{E_L}{d_L^{\eta}} - \frac{E_R}{d_R^{\eta}}$ and $d = \sqrt[\eta]{d_R^{\eta} - d_L^{\eta}}$
9. *if* $X > 1$ optimal position of the BNC $(X' - kd, Y)$
   elseif $X < 1$ optimal position of the BNC $(X' + kd, Y)$

D. Position-Aware BNC Placement Algorithm

PBP exhibits less complex formation compared to *DBP-I* and *DBP-F*. It has also linear computational complexity like *DBP-F*. But it considers the spatial coordinate information of nodes instead of relative transmission distance with respect to the BNC.

1) Considerations:

a) All nodes of a WBAN should be within the transmission coverage of the BNC.

The BNC should know the spatial coordinates of all nodes.

2) Working Mechanism: Like *DBP-I* and *DBP-F*, *PBP* does not has any confined initial BNC placement strategy. But, according to *PBP*, it is preferable to place the BNC within a WBAN. Its work principles are described in chronological order as follows.

Step 1) At first, a BNC is placed within a WBAN.

Step 2) After that, the BNC measures the relative communication distances of all available nodes of a WBAN based on their coordinates and considering itself as a center of coordinate system.

Step 3) Compute "UF" of all nodes based on their available energy (E) and relative communication distances (d_r).

Step 4) Then, BNC finds out the maximum "UF" from the available UFs of all nodes and estimates the factor "uf" of each node as follows:

for node j, uf_j

$$= \frac{\max\limits_{j:N_j \in U_j} \mathrm{UF} - \mathrm{uf}_j}{\text{maximum value of UF among all UF} \left(\max\limits_{j:N_j \in U_j} \mathrm{UF}\right)}.$$

Step 5) BNC finds out the maximum value of the factor "uf" from the available ones and normalize the factor "uf" of each node with respect to the maximum value, which lead us to χ. Here, each node has its own χ.

Step 6) Finally, all nodes multiply their own χ with their coordinates and divide the resultant with the number of node of the WBAN.

3) Algorithm: PBP:

Algorithm: PBP

1. *Place a BNC within a WBAN, say the point is* $P(X, Y)$
2. *Measure the relative distances* $(d_{r_1}, d_{r_2}, \ldots, d_{r_j})$ *of all body nodes* $(N_1, N_2, \ldots, N_j)$ *from the BNC. Here,* $\forall N\colon N_j \in U_j$
3. $\forall N\colon N_j \in U_j$
   Utility Factor, $UF(N_j) = \frac{available\ energy\ of\ node\ N_j}{(d_{r_j})^{\eta}}$
4. $\forall N\colon N_j \in U_j \quad uf_j = \frac{max_{j:N_j \in U_j} UF - UF(N_j)}{max_{j:N_j \in U_j} UF}$
5. $\forall N\colon N_j \in U_j \quad \chi_j = \frac{uf_j}{max_{j:N_j \in U_j} uf}$
6. $\forall N\colon N_j \in U_j$ *replace BNC at* (X_{new}, Y_{new})
   $\equiv \left(\frac{\sum_{j=1}^{N_j} (\chi_j . X_j)}{\#U_j}, \frac{\sum_{j=1}^{N_j} (\chi_j . Y_j)}{\#U_j}\right)$

IV. System Model

In this work, we consider the system model of [13] and [19], to evaluate our proposed algorithms along with the routing protocol. In [13] and [19], the system model was used to evaluate the performance, in terms of network longevity, of a cluster-based routing protocol, EAR-BAN and multihop routing protocol, PER, respectively. The used system model is depicted as follows.

A. Formation of the Body Area Network

We consider a WBAN of 175×175 cm [9], consisting of body nodes and a BNC. Here, we consider a human body which is kept standing and widely spread both of his hands in each side. We have taken into account both uniform and nonuniform random distribution (*Weibull Distribution* [21]) for allocating nodes on the human body. In *Weibull Distribution*, we consider scale parameter $A = 1$ and shape parameter $B = 5$.

B. Selection of Path Loss Model

To estimate the path loss between two transceivers, we use the log-distance path loss model of [7]. According to this formula, the path loss (PL_{dB}) at a distance d becomes

$$\mathrm{PL}_{dB} = \mathrm{PL}_{0,dB} + 10 * \eta * \log\left(\frac{d}{d_o}\right). \tag{3}$$

Here, $\mathrm{PL}_{0,dB}$ is the reference path loss at a reference distance d_0 and η is the path loss exponent. In this work, we consider the non-line-of-sight (NLOS) communication because of uneven surface of the human body and obstruction due to clothing and costumes. The following parameter have been used in the paper: $d_0 = 10$ cm, $\mathrm{PL}_{0,dB} = 48.8$ dB, and $\eta = 5.9$ [7].

C. Selection of Transceiver and Sensor

In this work, we consider that each node consists of a transceiver and a sensor. Here, we have considered the specification of a compact (4×4 mm) and energy limited transceiver, NORDIC nRF24L01 [22], where the operating frequency is 2.4 GHz at -85 dBm (0.1% BER) sensitivity and its maximum data rate is 1 Mbps. NORDIC nRF24L01 transceiver uses Gaussian frequency-shift keying (GFSK) modulation with four different programmable output power: 0, -6, -12, or -18 dBm at typical supply voltage of 3 V. In passive (standby-I) mode, it consumes about 6.6 mW and its changing mode power consumption, alternation between Tx mode and Rx mode, is about 24 mW.

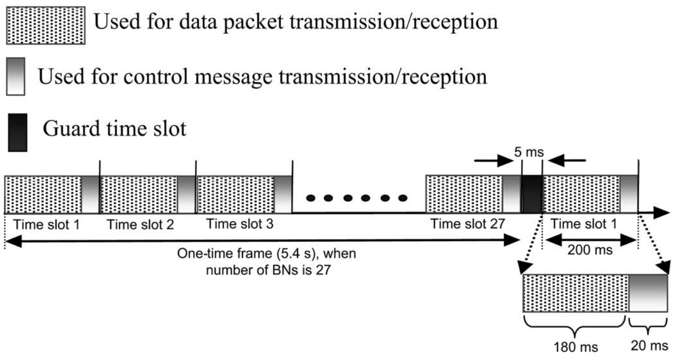

Fig. 7. Structure of the TDMA MAC.

To consider the energy consumption of a sensor, we use the specification of [23] as a standard where an ECG sensor having a size of $(2 \times 1.3)\ \mathrm{mm}^2$ consumed less than $12\ \mu\mathrm{W}$ at a data rate of 100 Kbps. Moreover, to run these nodes, we consider an implantable power source known as IOS-1 [24], which has the volume of $\sim 4.9\ \mathrm{mm}^3$ and the capacity of 1.7 mAh at ~ 1.5 V.

D. Selection of Media Access Control (MAC) Model

We have considered a time division multiple access (TDMA) MAC protocol of [13], [19], shown in the Fig. 7, where each of the nodes within the network got a time slot of 200 ms. So, the duration of a time frame or round of a WBAN becomes ($T_w =$ 200 ms $\times$ number of nodes). Here, each time slot is further divided into a 180-ms subslot, for data message transmission or reception, and a 20-ms subslot, for control message transmission or reception. Moreover in each 20 ms subslot, a 130 μs was allocated, for each transceiver, to alter between transmitting mode and receiving mode. A guard time slot is also included between two successive time frames for getting general control message from the BNC.

V. Performance Evaluation

In energy aware routing, one of the most used performance assessor metrics is the *Depletion Time*, which is defined as the time until the first node (or a fixed percentage of nodes) of a network depletes its available energy. So, a network with a higher depletion time has a higher lifetime, which shows its energy efficiency. Here, we considered the death of the first node of a WBAN, as the depletion time, to evaluate the performance of our proposed algorithms.

Commonly, the routing protocols, used in WBANs, can be classified (based on their data transmission manner) as multihop routing protocol and cluster-based routing protocol. In order to depict the performance of our proposed algorithms, here we have considered recent, relevant, and available form of both of these routing protocols: PER and EAR-BAN, whereas PER is considered as an example of multihop routing protocol and EAR-BAN is for cluster-based routing protocol.

Figs. 8 and 9 present the comparative performance of EAR-BAN, with and without effective BNC placement techniques within a WBAN. Here, a BNC is placed in one of three

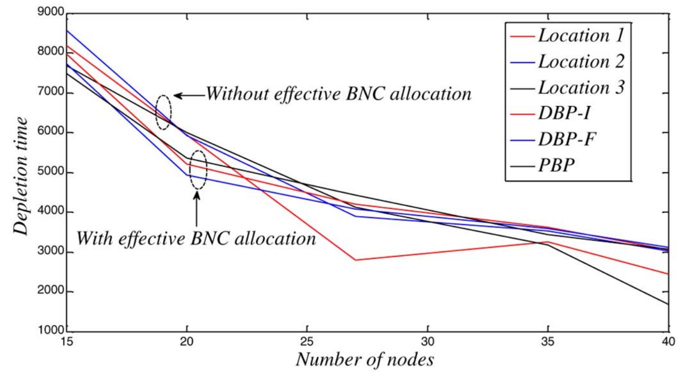

Fig. 8. Network lifetime with respect to the number of nodes by using EAR-BAN routing protocol, when nodes are uniformly distributed.

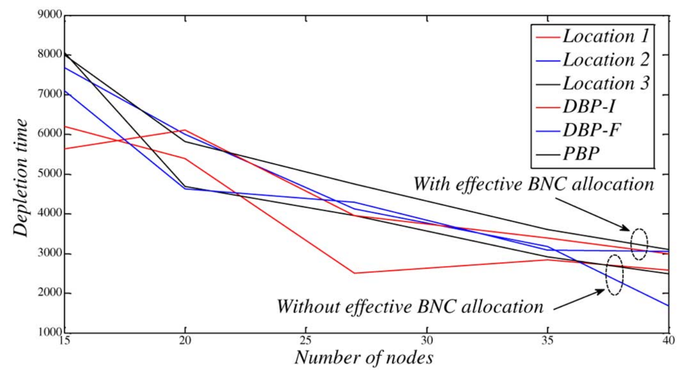

Fig. 9. Network lifetime with respect to the number of nodes by using EAR-BAN routing protocol, when nodes are nonuniformly distributed.

locations: waist (Location 1), upper limb (Location 2), and head (Location 3), shown in Fig. 1, at a time to show the impact of network longevity without having any BNC placement technique. On contrary, *DBP-I*, *DBP-F,* and *PBP* are used as effective BNC placement techniques to prolong network lifetime. We also consider both uniform and nonuniform distribution of nodes of WBANs, shown in Figs. 8 and 9, respectively. For EAR-BAN routing protocol, we account the similar system model of [13], where the available energy of nodes is randomly distributed within the range of 9–9.18 J. The simulation result of Fig. 8 shows that EAR-BAN, together with effective BNC placement algorithms and uniform node distribution, has not shown any cabalistic variation in performance because of using *DBP-I*, *DBP-F,* and *PBP*; but when the node distribution is nonuniform, *PBP* is outperforming than *DBP-I* and *DBP-F*, shown in Fig. 9. Here for nonuniform node distribution, although the energy efficiency, in term of depletion time, of *DBP-I* and *DBP-F* is similar, but *PBP* enhances the energy efficiency at maximum 20.4% than *DBP-F* and at maximum 29.7% than *DBP-I*.

On the other hand, Figs. 10 and 11 show the performance analysis of the multihop routing protocol, PER, for both uniform and nonuniform distribution of nodes of a WBAN, respectively. For PER routing protocol, we have considered the similar system model of [19], where the available energy of nodes is randomly distributed within the range of 3–9.18 J. In Figs. 10 and 11, we have shown the comparative performance of PER

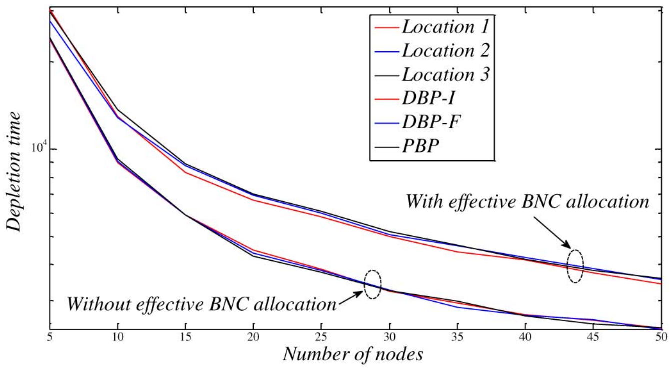

Fig. 10. Network lifetime with respect to the number of nodes by using PER routing protocol, when nodes are uniformly distributed.

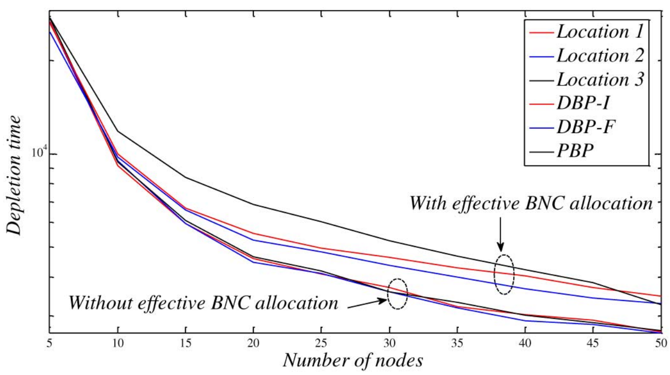

Fig. 11. Network lifetime with respect to the number of nodes by using PER routing protocol, when nodes are nonuniformly distributed.

with and without effective BNC placement algorithms within a WBAN. These simulation results show that our proposed BNC placement algorithms along with multihop routing protocol, PER, maximize the network lifetime more, compared to the cluster-based routing protocol, EAR-BAN. Although for PER, with effective BNC placement algorithms (*DBP-I*, *DBP-F,* and *PBP*) and uniform node distribution, energy efficiency because of using *DBP-I*, *DBP-F,* and *PBP* is almost similar, shown in Fig. 10; but for nonuniform node distribution, *PBP* outperforms compared to *DBP-I* and *DBP-F*, shown in Fig. 11. Here, the depletion time is considered as a measurement of energy efficiency. The simulation result of Fig. 11 shows that the energy efficiency of *DBP-I* is followed by *DBP-F* and with the increasing number of nodes of a WBAN their energy efficiencies are also increased. In all cases, *PBP* leads which increases the energy efficiency at maximum 23.2% than *DBP-F* and at maximum 20.5% than *DBP-I*, shown in Fig. 11.

A comparative analysis among these proposed algorithms is summarized in Table II. In this table, the number of physical alteration means how many times a BNC has to be displaced within a WBAN to find out its optimal location. We have accounted the term energy efficiency of each algorithm as the maximum differences, in network lifetime, between with and without effective placement of the BNC along with routing protocol. To estimate the energy efficiency of all of these algorithms, we have considered the same worst case scenario (Location 1), which one was considered in Section II. Message exchange complexity [27] defines how many times the BNC communicates with the sensor nodes; more specifically how many times the BNC broadcasts message to sensor nodes or the sensor node sends message to the BNC.

TABLE II
COMPARISON AMONG *DBP-I*, *DBP-F,* AND *PBP*

Motive	*DBP-I*	*DBP-F*	*PBP*
Initial requirement	Information of relative distances of all nodes	Information of relative distances of all nodes	Information of spatial coordinates of all nodes
Number of physical alteration (*l*)	multiple	once	none
Computational complexity	*O(l)*	*O(1)*	*O(1)*
Message exchange complexity	*O(l+1)*	*O(1)*	*O(1)*
Energy efficiency	Maximum 36.8%	Maximum 41.8%	Maximum 47.45%
Applications	EAR-BAN, PER	ETPA [25]	Kim *et al.* [26]

VI. CONCLUSION AND FUTURE WORK

In this paper, we have illustrated the importance of effective BNC placement within a WBAN to maximize the network longevity. Besides, to measure the lifetime expectancy of a node, we have shown the lacking in measurement of available metrics and thus proposed a new metric to fulfill the present demand. Based on our proposed metric, we have proposed three different algorithms, which are different in their requirements, formations, and result in different level of energy efficient and computationally efficient performances. The simulation results show the consistency of *PBP*, over *DBP-I* and *DBP-F*, in term of energy efficient and computationally efficient performances. In our next step, we will use specialized software, Castalia [28], to evaluate the performance of our proposed algorithms, in terms of reliability and control message overheads.

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