Optimization of Energy Efficient Relay Position for Galvanic Coupled Intra-body Communication

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***Abstract*—Implanted medical sensors and actuators within the human body will enable remote data gathering, diagnosis, and the ability to directly control drug delivery actuators. To establish the communication links through the body tissues, we adopt galvanic coupling that uses low frequency electrical signals of weak amplitude. In this paper, we propose a topology management strategy using Weiszfeld algorithm that attempts to minimize the transmission power of the body nodes by reducing the distance from the source nodes to pick-up points or relays that gather and forward the received information. It takes into account the unique propagation model of the electrical signals within the body at various tissue layers, which is completely different from over the air RF. Our algorithm considers separately the constraints of on-skin nodes and the implanted nodes, especially in terms of minimizing the energy for the latter, which cannot be easily retrieved and re-charged. It also considers the difference in specific bandwidth requirements for the applications running within the nodes, by moving relays closer towards the high data rate demanding regions. We show that by optimizing the position of the relay node, the energy consumption can be significantly improved to extend the lifetime of the intra-body network up to several years.**

I. Introduction

Recent developments in tiny sensor platforms have given rise to nodes that can be embedded within the body using minimally invasive procedures. These implanted sensors can potentially monitor and control various physiological processes in-situ autonomously. Hence, this technology is poised to revolutionize healthcare applications by creating a network of such connected miniature implants, which we term as an intra-body network (IBN). The IBN will allow the implants to (i) exchange information for self-configuration, and (ii) issue situation-based instructions to the drug delivery actuators without human intervention.

As radio frequency (RF) waves are strongly attenuated within the body and consume more power, we adopt galvanic coupling (GC) based IBN (GC-IBN), in which a pair of electrodes within a node inject a low strength, modulated signal to the body tissue. The difference in potential created by the induced field is detected by the electrode pair of a receiver node that demodulates the signal to retrieve the data. The embedded nodes are expected to serve continuously over the application lifetime without any redundancy in their deployment. Thus, reducing the energy consumption and extending the battery life of body nodes in general, and implanted nodes in particular, are the key challenges in GC-IBN design. This paper takes the first steps towards identifying the location for the data aggregation functions, enabled by 'relay' nodes from a viewpoint of energy minimization and meeting application-requirements.

The potential for GC-IBN in establishing IBNs has been demonstrated using the tissue channel characterization studies in [1], [2]. However, there have been limited efforts in influencing the topology of the IBN by utilizing the channel characteristics, which are different from classical over the air RF propagation. The energy consumption in such networks depends not only on the arrangement of nodes, in terms of the relative spatial distance but also on the type of tissue and the depth within the tissue. An energy efficient network topology should minimize the path length between the transmitter and receiver (that determines the path loss) and in-turn the transmission power (Pt). For instance, an implant node close to the sink (eg., node $N5$ to relay R distance in Fig.1.(b)), can use low Pt to communicate with the sink, while a distant node (eg., node $N2$ to R link in Fig.1.(b)) requires high values of Pt. In this paper, we analyze the parameters that influence the shortest path length towards extending the battery life of nodes. The main contributions of this paper are as follows:

1) We estimate the bounds on Pt for each node, given the specific tissue it is embedded in, while meeting both reliability and tissue safety constraints.

2) We propose a multi-variate optimization approach based on Weiszfeld algorithm in determining the position of on-skin aggregators or relays that serve a cluster of body nodes. The proposed approach incorporates variations in the heterogeneity of data rate, the position of nodes in tissues, and the path loss of the body channel. Our objective function is designed to minimize the net signal flow through the tissues, and thereby maximize network lifetime.

The paper is organized as follows. Sec.II, analyzes the related work on optimizing topology for energy efficiency. The system model is presented in Sec.III. Sec.IV formulates the positioning problem and presents an optimal solution. Sec.V evaluates the results obtained and Sec.VI concludes the paper.

II. Related Background

The problem of determining the location of a central facility has been solved for different scenarios, including manufacturing plants, fire stations and wireless networks. Specifically in wireless sensor networks (WSNs), several sink localization schemes have been proposed including positioning at the center of the cluster or at the points of intersection of clusters. [3] proposes a topology control scheme that attempts to vary the number of reachable neighbors by adjusting its Pt, which is extended for fading environments in [4]. In [5], a center point that lies at a minimum distance to all nodes is determined as the location of the base station. The total

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energy cost is minimized in [6] by achieving energy balance in the network. However, these existing positioning techniques cannot be applied for GC-IBN for the following reasons.

1. GC-IBN is distinguished from other applications by the tissue safety requirement. The maximum power transferred though the tissues is required to be lower than the safe level suggested by ICNIRP [7].

2. The location of aggregation point in a wireless network is determined with the objective of extending coverage to a given area with random distribution of mobile nodes. For such a network, the default location of the aggregation point at the center of the cluster would be ideal. However, node locations in IBN are influenced by the medical applications with high probability of node concentration in small pockets of area (Eg. neuro-muscular stimulators) with multiple such high density regions. A general relay placement at the center of a given area would perhaps require higher transmission energy over the entire application.

3. While classical WSN nodes use free space as the medium of communication, GC-IBN nodes operate in a heterogeneous environment. Given the choice of tissue in which they are embedded, there is variance in the path-loss. Thus, energy conservation in implants that are not easily re-chargeable should be given higher priority over the surface nodes. Also, the tissue channel requires asymmetric channel characterization [1], [2].

4. The lifetime of a cluster in the GC-IBN begins from the time of network installation to the instant that requires an invasive surgery to replace the battery of any node in that cluster. This is in contrast to classical WSNs where the lifetime can be extended until atleast a reduced subset of sensors is available, given the redundancy that typically exists in their deployment. In addition to non-redundant deployment, GC-IBN comprises of body regulatory actuators alongside the sensors, whose death is catastrophic.

5. All GC-IBN nodes are battery operated, which is in contrast with the wired sink in WSN that functions without energy limitation. Therefore, the power consumption in relays and nodes have to be analyzed jointly.

6. Existing WSN protocols are designed for many to one communication. This is suitable for sense only applications and not for CPS feedback based sense-react systems.

To the best of our knowledge, the central facility or relay location problem have not been solved in heterogeneous intra-body networks. This paper provides the first relay positioning technique that is suitable for GC-IBN.

III. GC-IBN System Model

The objective of the GC-IBN is to enable communication among the body nodes (e.g., blood glucose sensors and insulin pumps) that might be distributed throughout the body either as implants or as surface nodes. The body nodes transfer the sensed physiological data to the sink, and the latter in-turn generates directives and controls the actuators for neural/muscular stimulation, fluid control, pain control or drug delivery. The sink also acts as a gateway for the IBN to exchange health data and control information with an external control point, such as authorized caregivers. GC-IBN is a short range network

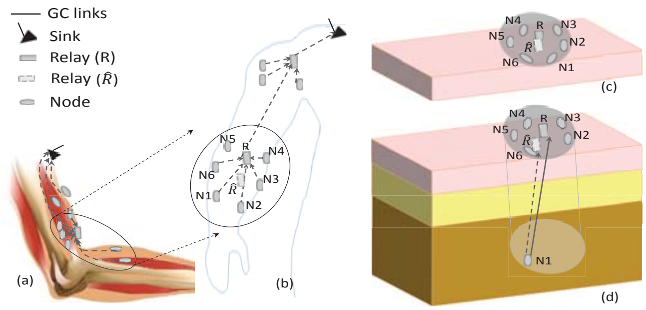

Fig. 1. First hop topology in GC-IBN (a) GC-IBN in human arms (b) Planar topology of GC-IBN (c) Three dimensional (3D) topology with all surface nodes (d) 3D topology with node N1 implanted in muscle

confined within the body, with a maximum reliable direct communication distance of a few tens of centimeters [1]. Direct and reliable communication between two nodes is feasible if their separation is less than the maximum achievable distance of the tissue path that we term as the threshold distance (D_{Th}). However, if the nodes are separated more than D_{Th}, then they require multiple hops for reliable communication. Provision of multiple hops using relays would reduce the path loss and provide connectivity for unreachable nodes from sink. Fig.1.(b) illustrates the role of two relays in connecting the nodes to the sink. In this paper, we assume that multi-hop paths can be set using dedicated on-surface relay transceivers in order to provide connectivity in GC-IBN. Dedicated surface relays, albeit at the overhead of additional network components, enable scalable and long-term network operation.

In this paper, we consider a set of iid nodes forming a GC-IBN in human arm that are placed either on the surface or implanted (refer Fig.1.(a)). A cluster of N nodes reachable from a point in single hop are clustered with a dedicated relay (refer R in Fig.1.(b)). The relay forwards data to the sink either in single hop or multiple hops. The position of a node Nm, $m \in \{1,..,N\}$ is specified as $\{L_m^{iz} : L \in \Re^2 \ \forall i \in \{S,M\}\}$, with $i = \{S\}$ for surface nodes (eg. $N1$ in Fig.1.(c)) and $i = \{M\}$ for implants (eg. $N1$ in Fig.1.(d)). Note that the tissue region and depth of implant in that tissue form a three dimensional coordinate system. For instance, $T = \{M\}$ and $Z = \{z\}$ indicates the position of the implant in muscle at z units depth from fat to muscle interface. The position of each node is assumed to be fixed as specified by medical professionals. We ignore the implants in fat and bone as the sensors are not commonly placed in these tissues.

The energy consumption in a node is contributed by multiple processes such as sensing (for sensors only), actuating (for actuators only), signal processing, transmission and reception. The power consumed by a node Nm is given by Pt_m=$Pt_{\lambda m}$+$Pt_{\xi m}$, where $Pt_{\lambda m}$ is a distance dependent component and can be minimized by reducing the communication distance. Hence, we focus on this distance-dominated energy consumption in this work. $Pt_{\xi m}$ is the distance independent component consumed for other transceiver processes, which is assumed to be constant for rest of this paper. The data rate requirement differs among the body nodes, which we distinguish by specifying the required data rate η_m>0, $\forall m \in \{1,..,N\}$ for each node. The distance between a pair of nodes m and n positioned at L_m^{iz} and $L_n^{jz'}$ is determined as

$$d_{mn}^{iz-jz'} = \parallel L_m^{iz} - L_n^{jz'} \parallel \tag{1}$$

where d is the distance from m to n through the $(iz\text{-}jz')$ path, $i, j \in \{S, M\}$, $z, z' \in \{0, .., \text{tissue thickness}\}$, i denotes the tissue where node m is positioned at depth z, j denotes the tissue of node n at depth z' and $(\| \,.\, \|)$ is the Euclidean norm. The $(iz\text{-}jz')$ path definition and the corresponding channel gain $g_{mn}^{iz\text{-}jz'}$ through various tissue paths are obtained using the multi-layer tissue model derived for human arm in [1]. Direct and reliable communication between two nodes is feasible if the distance between them ($d_{mn}^{iz\text{-}jz'}$) is less than the maximum achievable threshold distance ($D_{Th}^{iz\text{-}jz'}$) of $iz\text{-}jz'$ path i.e.,

$$d_{mn}^{iz\text{-}jz'} \leq D_{Th}^{iz\text{-}jz'}, \forall i, j \in \{S, M\} \tag{2}$$

The instantaneous received signal to noise ratio (SNR) between two nodes m and n through path $iz\text{-}jz'$, represented as $\delta_{mn}^{iz\text{-}jz'}$, is estimated using the link budget computation as

$$\delta_{mn}^{iz\text{-}jz'} = \frac{Pt_{\lambda m} \cdot g_{mn}^{iz\text{-}jz'}}{N_o^{iz\text{-}jz'}.\triangle f} \tag{3}$$

where $N_o^{iz\text{-}jz'}/2$ is the Gaussian distributed noise P.S.D in path $(iz\text{-}jz')$ with zero mean and variance φ, $\triangle f$ is the receiver bandwidth and $Pt_{\lambda m}$ is the transmitted power by node m. The SNR required for a reliable communication that offers the desired bit error rate can be determined for a given modulation technique. Assuming the Phase Shift Modulation (PSK) for communication through GC links, the bit error probability P_b^{mn} from node m to node n [8] can be estimated as,

$$P_b^{mn} \leq \frac{1}{2} Q \sqrt{2 \, log_2 M' \left(\frac{E_b^m}{N_o^{iz\text{-}jz'}} \right)}.sin(\frac{\pi}{M'}) \tag{4}$$

where $M' = 2^{m'}$ is the number of modulation signaling states, m' is the number of bits transmitted per symbol, $E_b^m/N_o^{iz\text{-}jz'}$ expressed as $\delta_{mn}^{iz\text{-}jz'}.B_{mn}/\eta_m$ is the bit energy to noise ratio, η_m is the data rate required for communication from m to n and B_{mn} is channel bandwidth. The maximum distance $d_{max}^{iz\text{-}jz'}$ in a tissue path $iz\text{-}jz'$ that offers the desired error probability, $\hat{P}_b$ is the threshold distance, $D_{Th}^{iz\text{-}jz'}$ of path $iz\text{-}jz'$ beyond which the $P_b^{mn} > \hat{P}_b$. We assume that the relay is positioned on-surface at L_R^S with zero depth (z=0) and is reachable from all the N nodes in cluster via single hops. Fig.1 shows the resulting cluster (shaded area) with two possible positions of the relay and the first hop links from nodes to R.

IV. Relay Positioning Problem

Given a set of nodes forming a cluster in human arm, the objective is to determine the position of R that brings Pt_λ to a minimum required level, thus prolonging the battery life. When a node m at L_m^{iz} is located close to L_R^S (or briefly L_R), enabling smaller path-loss in m to R communication, the $\delta_{mn}^{iz\text{-}S}$ experienced will be higher than that required for achieving $\hat{p_b}$. Correspondingly the $Pt_{\lambda m}$ can be minimized to a level that is sufficiently high for a required $\hat{P_b}$. An optimally positioned L_R would minimize the communication distance from nodes and consequently would reduce the energy consumed in multiple (or even all) nodes in a cluster. Therefore, the choice of L_R plays a critical role in influencing the channel performance in terms of SNR, BER and energy consumption. For example in Fig.1.(c), the total link length and hence the path loss experienced with relay at $\hat{R}$ is significantly lower than the relay positioned at R as demonstrated in Sec.V.

In this section we estimate an optimum position of the relay, $\hat{L_R}$ that ensures minimum sum of link distances, i.e., $d_{iz\text{-}S}^{mR}, \forall m \in \{1, .., N\}$, $\forall i \in \{S, M\}$, $\forall z \in \{0, .., \text{tissue thickness}\}$ as given below.

$$\hat{L_R} = argmin_{L_R} \sum_{m=1}^{N} \| L_m^{iz} - L_R^S \| \tag{5}$$

where $i \in \{S, M\}$ and S denotes the on-skin position of relay. In addition to minimizing the distance between the node and R, the relay position estimation problem should also consider other properties of GC-IBN, as explained below:

• **P1. Tissue safety:** The transmission power should be constrained by the permitted safe level of induced field Pt_s in live tissues [7], i.e.,

$$Pt_m^{max} \leq Pt_s \text{ or } Pt_{\lambda m} \leq Pt_s - Pt_{\xi m}, \forall m \in \{1, ..N\} \tag{6}$$

• **P2. Bounds on Pt and E_b:** Next, we determine the bounds on Pt_m of a node m as follows. With an initial energy store of $E_0(m)$ in node m, in order to extend the node life more than zero units of time, the condition $E_H(m) \leq E_0(m)$ should be satisfied, where $E_H(m)$ is the total energy consumed over a period H sec. $E_H(m)$ can be estimated as

$$E_H(m) = \frac{E_b^m \, \eta_m \, H}{\triangle f.log_2 M'} \tag{7}$$

Using (6) & (7), the upper bound on Pt_m can be set as Pt_{max}=$min(Pt_s, E_0/H)$, for the expected node life H. The corresponding maximum E_b (E_b^{max}) can be determined as

$$E_b^{max}(m) = Pt_m^{max} \triangle f.log_2 M/\eta_m \tag{8}$$

The relation in (7) indicates that lower energy per bit (E_b^m) and the corresponding lower $Pt_{\lambda m}$ would result in lower energy consumption $E_H(m)$ over a period H sec. Hence, larger H can be obtained for lower values of E_b^m. However, Pt_m should be maintained at a sufficient minimum level (Pt_m^{min}), that offers reliable communication with $P_b \leq \hat{P_b}$. Hence, the lower bound on Pt_m becomes

$$Pt_m^{min} = \frac{\hat{\delta}^{iz\text{-}jz'} N_o.\triangle f}{g_{mR}^{iz\text{-}jz'}}, \forall m \in \{1, .., N\} \tag{9}$$

• **P3. Energy cost of implants:** An implant has very limited energy source, while the surface node can have potentially more energy availability. Hence, the overall energy consumption in implants must be less than that of the surface nodes. This requires the relay position to be closer to the implants, satisfying the following condition.

$$\sum_k d_{kR}^{Mz\text{-}S} < \sum_s d_{sR}^{Sz\text{-}S} \tag{10}$$

$\forall k \in \{1, .., K\}, s \in \{1, .., N\text{-}K\}$, where K is the number of implants, $(N\text{-}K)$ is the number of on-skin nodes, $Mz\text{-}S$ is the in-muscle position at depth z to on-skin at depth zero path and $Sz\text{-}S$ is the on-skin at depth z to on-skin at depth zero path. Note that we use depth zero for relay position per the assumption made above.

• **P4. Heterogeneity from data rate:** The difference in required data rate η_m among nodes is an added challenge in determining the relay position. Assuming the same modulation technique among all the nodes, the ones with higher η_m needs longer duty cycles and thus consume more energy. L_R closer to nodes with high η_m would extend their life. For nodes m and n, with η_m and η_n respectively, if $\eta_m > \eta_n$, then the following condition must be satisfied.

$$d_{mR}^{iz\text{-}S} \leq d_{nR}^{iz\text{-}S},\ \forall \eta_m > \eta_n \tag{11}$$

Problem Formulation: To satisfy the requirement in (10) and (11), the problem of estimating $\hat{L_R}$ can be solved using weighted distance metric w_m that supplement the path loss metric with appropriate priority derived based on tissue hosting the node and its required data rate η_m. This weighted distance combines the above listed goals into a single relay positioning problem that can be formally stated as follows. For a set of N body nodes $\{L_m^{iz} : L_m \in \Re^2, \forall m \in \{1,..,N\}, i \in \{S,M\}\}, z \in \{0,.., \text{tissue thickeness}\}$, with given $w_m > 0$, estimate $\hat{L}_R$ that minimizes the total sum of weighted distances separating R and nodes given by $C(L_R) = \{\sum_{m=1}^{N} w_m d_{mR}^{iz\text{-}S} : L_m, L_R \in \Re^2\}$, i.e.,

$$\begin{aligned}
&\text{Minimize} && C(L_R)\\
&\text{subject to} && 1.\ d_{mR}^{iz\text{-}S} \leq D_{Th}^{iz\text{-}S}\\
& && 2.\ \frac{\hat{\delta}^{iz-S} N_o^{iz\text{-}S} \triangle f}{g_{mR}^{iz\text{-}S}} \leq Pt_m \leq min\{Pt_s, E_0/H\}\\
& && 3.\ \sum_k d_{kR}^{iz\text{-}S} < \sum_s d_{sR}^{iz\text{-}S}\\
& && 4.\ d_{mR}^{iz\text{-}S} \leq d_{nR}^{iz\text{-}S},\ \forall \eta_m > \eta_n
\end{aligned}$$

$\forall m,n \in \{1,..,N\},\ k \in \{1,..,K\},\ s \in \{1,..,(N\text{-}K)\},\ i,j \in \{S,M\}$, where, K is the number of implanted nodes. This problem resembles a single facility location problem, or more specifically the *classical Fermat-Weber problem* with unsplittable demands as we intend to allocate one relay per cluster. We use the following related theorems from [9] in the solution to this problem.

Theorem 4.1: The relay position problem can be solved using heuristic search algorithms that yield an approximation in polynomial time which is otherwise considered NP-hard.

Theorem 4.2: For non-collinear nodes with $L_m^{iz} \forall m \in \{1,..,N\}, i \in \{S,M\}$, $C(L_R)$ is non-negative and strictly convex and the minimum can be achieved at an unique L_R.

If $\{L_1^{iz},..,L_N^{iz}\}$ are collinear, then $C(L_R)$ can be obtained using L_1 approximated weighted median. We consider the non-collinear positions of nodes in this paper. We propose our relay position optimization algorithm in the following section.

L_R **Optimization using Weiszfeld Algorithm (LOWFA):** In this section, we devise a relay position optimization technique using Weiszfeld algorithm (refer Algorithm.1) that places R closer to all the nodes in such a way that the total distance from all the nodes to $\hat{L}_R$ is minimum and the properties $P1, P2, P3$ and $P4$ are satisfied. Our proposed algorithm begins with the computation of the initial position of relay that

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Algorithm 1 Estimation of $\hat{L}_R$ and $Pt_{m\lambda}$

Input: Set $A = \{L_m^{tz}(x_m, y_m), \eta_m\}, \forall m \in \{1,..,N\},\ t \in \{S,M\}$, Gain $g_{m,R}^{tz\text{-}S}, \forall t \in \{S,M\}, \forall m \in \{1,..,N\}$, safe power Pt_s, BER probability P_b^{mR}, noise variance φ, expected node life $H(m)$ (secs), battery capacity $E_0(m)$, distance independent transmitted power Pt_ξ, implants priority α, threshold distance $D_{Th}^{tz\text{-}S} \forall t \in \{S,M\},\ z \in \{0,.., \text{tissue thickness}\}$ & receiver BW, $\triangle f$.
Output: $\hat{L}_R$, Pt_λ, and node life
Initialization:
Assign it =1, $step(it) = \infty$ ▷ % iteration & step size %
$C_{gc} = \{\frac{1}{N}\sum_{m=1}^{N} L_m^{tz}(x), \frac{1}{N}\sum_{m=1}^{N} L_m^{tz}(y)\}$
Assign $L_R(it) = C_{gc}$ ▷ % Initial relay position%
Compute bound $Pt_\lambda^{max} = min\{Pt_s, E_0/H\} - Pt_\xi$
LOWFA Algorithm:
for $m = 1,..,N$ **do**
  $w_m = \alpha^{(t+z-1)} . \frac{\eta_m}{\sum_{x=1}^{N} \eta_x}$
  $dw_m = \frac{w_m}{\sum_{m=1}^{N} w_m}$ ▷ % Compute node weights%
end for
while $step(it) > \epsilon$ **do**
  for $m = 1,..,N$ **do**
    $d_{mR}^{tz\text{-}S}(it) = \parallel L_m^{tz} - L_R(it)^{(WF)} \parallel \forall t \in \{S,M\}$
  end for
  $L_R^{it+1} = \sum_{m=1}^{N} \frac{dw_m}{d_{mR}^{tz\text{-}S}(it)} . \left(\sum_{m=1}^{N} \frac{1}{d_{mR}^{tz\text{-}S}(it)}\right)^{-1}$
  $Step(it) = L_R^{it+1} - L_R^{it}$; Increment it
end while
Obtain $g_{mR}^{(tz\text{-}S)}$ from [1] using $\hat{L}_R$
$Pt_{\lambda m}^{min} = \left(\frac{\hat{\delta}^{tz\text{-}S} N_o^{tz\text{-}S} . \triangle f}{g_{mR}^{tz\text{-}S}}\right)$ ▷ % Power consumption%
for $m = 1,..,N$ **do**
  if $(Pt_{\lambda m}^{min} > Pt_\lambda^{max})$ **then**
    $\{A\} = \{A\}/\{N_m\}$ ▷ % Remove Nm from A%
  end if
end for

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is chosen to be the centroid of the cluster, C_{gc} calculated as

$$C_{gc} = \{\frac{1}{N}\sum_{m=1}^{N} L_m^{iz}(x), \frac{1}{N}\sum_{m=1}^{N} L_m^{iz}(y)\} \tag{12}$$

where x and y are the coordinates of node position in each dimension without considering the depth.

Computing Node Weights: In order to enable the algorithm to adapt based on the heterogeneity in nodes and tissue paths and to enable higher energy saving in implants, our algorithm proceeds with prioritizing the nodes based on node weights. The weights are computed using a factor $\alpha \in [1, 10]$ that sets higher priority for implants based on the expected difference in energy consumption between the implanted and surface nodes. For instance, when the set $\{S,M\}$ is enumerated as $\{1,2\}$, α=1 sets equal priority for implant and on-skin nodes while α=10 sets very high priority for implants. The node weights comprising α and tissue position of the node is computed as w_m=$\alpha^{(T+z-1)}$. As defined by property $P4$, moving the relay closer to nodes with high η_m would help maintaining uniform battery level among nodes albeit with different data rate requirement. To achieve this, we include the unity based normalization of η_m in estimating the node weights as,

$$w_m = \alpha^{(T+z-1)} . \frac{\eta_m}{\sum_{x=1}^{N} \eta_x} \; \forall m \in \{1, .., N\} \tag{13}$$

The normalized node weights become $dw_m = \frac{w_m}{\sum_{m=1}^{N} w_m}$. After estimating the node weights, we calculate the euclidean distances between $L_R(it)$ (initially at C_{gc}) and the nodes as $d_{mR}^{iz\text{-}S} = \parallel L_m^{iz} - L_R^{it} \parallel$. Using the computed weights and $d_{mR}^{iz\text{-}S}$, the optimal relay position is computed iteratively as,

$$L_R^{it+1} = \sum_{m=1}^{N} \frac{dw_m}{d_{mR}^{iz\text{-}S}(it)} . \left(\sum_{m=1}^{N} \frac{1}{d_{mR}^{iz\text{-}S}(it)} \right)^{-1} \tag{14}$$

where L_R^{it} is the relay location estimate at the it^{th} iteration. This step repeats until the difference (indicated as Step) between the current and the previously estimated L_R is greater than the preset limit ϵ. $Pt_{\lambda m}$ is computed using (9) and is verified to be in bounds defined in $P2$. Any node that does not obey the power bounds is removed from the cluster and is to be included in the neighboring clusters. The results of the optimization procedure is analyzed below using the transmission power consumption as the evaluation parameter.

V. Performance Evaluation

Conventionally in wireless networks, the central facility location is assumed to be a set of fixed possible points such as the center of the area (C_f) or the center of the minimum possible boundary in the case of location aware networks that is determined as the center of extreme points (C_e) [5]. In this section, we compare the total energy conservation achieved by positioning relay at the optimal positions obtained using the proposed optimization scheme using LOWFA algorithm (L_R^{WF}) and the conventional positions at the center of cluster ($L_R^{C_f}$) and at the mid-point ($L_R^{C_e}$) between the extreme nodes.

We evaluate the proposed LOWFA algorithm in Matlab for two different scenarios. The first scenario has a cluster of homogeneous distribution of nodes positioned in the same tissue with similar data rate requirement. This scenario is used to demonstrate the effective node life extension ability of the proposed algorithm. The second scenario has heterogeneous nodes that are either attached on-surface or implanted in muscle with different data rate requirement and is used for illustrating the effectiveness and adaptability of the proposed solution for heterogeneous network conditions.

Scenario.1 Homogeneous Node Distribution We consider six nodes, whose locations are randomly chosen in the cluster of dimension $25 \times 15\,\text{cm}$ (refer Fig.1(c)). All the nodes are assumed to be in the same tissue (T=1) in this scenario with uniform data rate requirement (η=1). To proceed with the analysis, we use the galvanic coupled tissue model presented in [1] to measure the channel gain with the following assumptions. The frequency of operation is set at $100\,\text{KHz}$, N_o as $0.01\,\mu\text{W}$, E_S as $5\,\text{cm}$, E_L as $1\,\text{cm}$ and D as $d_{mR}^{iz\text{-}S}, \forall m \in \{1, .., m\}$. The effectiveness of the proposed LOWFA algorithm is quantized in terms of resulting nodes to relay distances and averaged for 50 simulations in Fig.2. The average total node to R distance d_{mR}^{WF} obtained using L_R^{WF} ($\hat{R}$ in Fig.1(c) & d_{mR}^{WF} in Fig.2) is the lowest (36.5 cm) compared to the conventional relay positions at $L_R^{C_f}$ & $L_R^{C_e}$ (refer d_{mR}^{Cf} & d_{mR}^{Cf} in Fig.2) with $\approx 41.64\,\text{cm}$. Thus, the relay position obtained using LOWFA algorithm effectively minimizes the total distance traveled by signal through the tissue by moving the relay closer to the nodes.

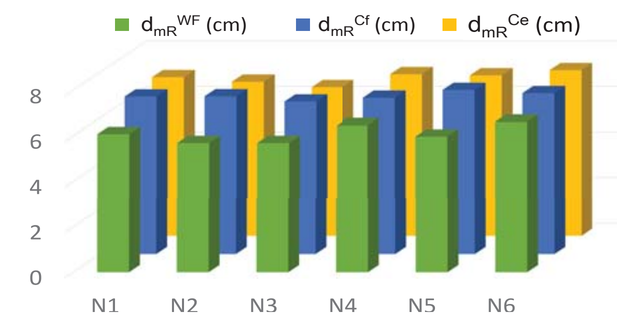

Fig. 2. Node to relay distances using LOWFA vs conventional techniques

The power conservation achieved in each node is presented in Table.I. Pt_λ given is calculated assuming the minimal required SNR to be 7. The node life is estimated assuming a battery rating of $240\,\text{mAh}$ and 10% duty cycle. As expected, the relay position at L_R^{WF} extends the lives of all the nodes with a minimum of 25 days upto a maximum of 100 days. The battery life extension achieved is significantly higher than the conventional schemes and therefore becomes a critical component in GC-IBN topology optimization.

Scenario.2 Heterogeneous Node Distribution Having established the effectiveness of LOWFA algorithm, we proceed with the algorithm evaluation considering heterogeneous nodes that are positioned in different tissues with non-uniform bandwidth requirements η. We follow the simulation set-up same as that of homogeneous scenario with six nodes and the relay positioned at L_R^{WF} ($\hat{R}$ in Fig.1(d)). Initially, we assume that node $N1$ is implanted in muscle (refer Fig.1(d)) with T_1=M & z_1=0 and that the other nodes are on surface with T_m=S & z_m=0, $\forall m \in \{2, .., 6\}$. We assume equal bandwidth requirement η_m=1, $\forall m \in \{1, .., 6\}$ for all the nodes. From the resulting node to relay distance $d_{mR}^{i\text{-}S}, \forall i \in \{S, M\}$, it is observed that the $d_{1R}^{M\text{-}S}$ obtained from $N1$ to R is significantly lower than the $d_{mR}^{S\text{-}S}, \forall m$=$\{2, .., 6\}$ as depicted in Table.II. This ensures minimum Pt_λ for $N1$, as desired for an implant in muscle. The corresponding battery life of $N1$ is extended to $23.5\,\text{years}$ that is atleast $1\,\text{year}$ more than the rest of the nodes. On average, an improvement of $4\%\,to\,17\%$ in battery life is

TABLE I. Comparison of $Pt_{m\lambda}$ (μW) & node life (days) in scenario 1 with relays at L_R^{WF}, $L_R^{C_f}$ & $L_R^{C_e}$

	N1	N2	N3	N4	N5	N6
Pt_λ^{WF}	1.6	.84	.82	1.7	1.5	1.9
$Pt_\lambda^{C_f}$	2.1	2.1	1.9	2.0	3.3	2.9
$Pt_\lambda^{C_e}$	2.2	2.0	1.9	2.9	2.8	3.5
Life^{WF}	8446	8514	8515	8440	8455	8422
Life^{C_f}	8407	8407	8426	8415	8305	8346
Life^{C_e}	8398	8415	8426	8346	8351	8293

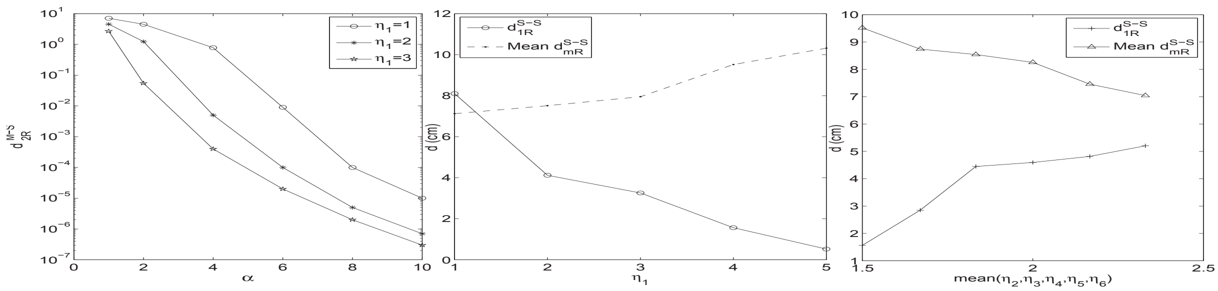

Fig. 3. (Left) d_{1R} vs α for varying η; (Mid) d_{1R} and mean d_{mR} for varying η; (Right) Change in d_{1R} with varying mean η_m

TABLE II. COMPARISON OF MEAN $d^{i\text{-}S}_{mR}$ (CM), $Pt_{\lambda m}$ (μW) & NODE LIFE (YEARS) AT L^{WF}_R, $T = [2111111], \eta = [111111]$ & $\alpha = 4$

	N1	N2	N3	N4	N5	N6
$d^{i\text{-}S}_{mR}$ (WF)	0.4	9.1	9.0	8.5	7.8	9.3
Pt^{WF}_{λ}	0.1	14.9	13.3	10.6	4.2	21.1
Life^{WF}	23.5	20.44	20.7	21.3	22.5	19.4
Improvement		13%	12%	9%	4%	17%

TABLE III. INFLUENCE OF α IN $d^{i\text{-}S}_{mR}$; $T = [211111]$ & $\eta = [111111]$

α	N1	N2	N3	N4	N5	N6
2	3.4	6.6	9.6	6.1	6.1	9.3
4	0.4	9.1	8.9	8.5	7.8	9.3
10	1E-3	13.3	15.6	14.4	7.9	10.1

achieved for $N1$ compared with all the other nodes.

In the above analysis in Table.II, α is set as 4. Table.III illustrates the influence of α on $d^{i\text{-}S}_{mR}$. When α=2, the $d^{M\text{-}S}_{1R}$ is minimized by a factor ranging from 0.80 to 1.82 when compared with other nodes. When α is increased to 4, the average $d^{M\text{-}S}_{1R}$ obtained is $0.4\,\mathrm{cm}$, which is reduced by ≈ 18.5 to 22.3 times than $d^{S\text{-}S}_{mR}, \forall m$=$\{2,..,6\}$. For α=10, the average $d^{M\text{-}S}_{1R}$ is only $1e$-3 which is closer to zero and this makes the decrease in $d^{M\text{-}S}_{1R}$ 7899 to 15600 times the other nodes. Thus, the distance dependent power consumption of implant can be controlled against the on-surface nodes by varying α. This effect is further emphasized with respect to changes in η in Fig.3(left). For the same T as above, when η_1 is increased from 1, indicating same traffic requirements as other nodes, to 3 where $N1$ has 3-fold increase in traffic, the corresponding d^{WF}_{1R} obtained is further reduced to decrease energy consumption due to increase in traffic. Thus the proposed algorithm intends to bring the relay closer to the node with higher bandwidth requirement in order to avoid quick draining.

With α being unchanged, the effect of varying η for nodes in the same tissue is analyzed in Fig.3(mid). Considering node $N1$, when η_1 is increased from 1 to 5, the average $d^{S\text{-}S}_{1R}$ reduces from $8\,\mathrm{cm}$ to $0.3\,\mathrm{cm}$, albeit with an average increase in $d^{S\text{-}S}_{mR}$ of other nodes by $\approx 1.5\,\mathrm{cm}$. Thus $Pt_{\lambda m}$ is reduced for nodes with higher η_m and increased for nodes with lower η_m. The bandwidth requirement based relay positioning also helps in establishing energy balance among co-located nodes. Fig.3(right) illustrates the change in the optimized distance of the node $N1$ with respect to the change in mean $\eta_m, \forall m$=$\{2,..,6\}$ of other nodes in the same cluster. For η_1=5, when the mean $\eta_m, \forall m = \{2,..,6\}$, increases from 1 to 2, the minimized $d^{M\text{-}S}_{1m}$ value rises from $1.6\,\mathrm{cm}$ to $4.8\,\mathrm{cm}$. This indicates that the priority given to a node for a high η declines with the rise in mean η of other nodes in cluster, achieving energy balance reasonably.

VI. CONCLUSIONS

The proposed relay positioning strategy for GC-IBN using Weiszfeld algorithm demonstrates the potential of energy saving in embedded implants by bringing the relay closer to the IBN nodes. An effective increase in the life of implants is demonstrated for varying node demands by comparing the results of the proposed strategy with conventional relay positioning schemes in classical WSNs. The algorithm is adaptive to the variations in the tissue where the node is located, the individual bandwidth requirement and the average bandwidth requirement of all the nodes in cluster. The proposed relay positioning strategy will enable optimized topology design for the galvanic coupled intra-body communication.

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