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Green Wireless Body Area Nano-networks: Energy Management and the Game of Survival

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***Abstract*—In this paper, we envisage the architecture of Green Wireless Body Area Nano-network (GBAN) as a collection of nano-devices, in which each device is capable of communicating in both the molecular and wireless electromagnetic communication modes. The term *green* refers to the fact that the nano-devices in such a network can harvest energy from their surrounding environment, so that no nano-device gets old solely due to the reasons attributed to energy depletion. However, the residual energy of a nano-device can deplete substantially with the lapse of time, if the rate of energy consumption is not comparable with the rate of energy harvesting. It is observed that the rate of energy harvesting is non-linear and sporadic in nature. So, the management of energy of the nano-devices is fundamentally important. We specifically address this problem in a ubiquitous healthcare monitoring scenario and formulate it as a cooperative Nash Bargaining game. The optimal strategy obtained from the Nash equilibrium solution provides improved network performance in terms of throughput and delay.**

***Index Terms*—Nano-network, Nash Bargaining, Ubiquitous healthcare.**

I. Introduction

The rapid advancement in the field of nanotechnology in the last two decades has provided us the engineering tools to design and fabricate nano-structured components (of size 1-100 nanometers) such as nano-sensors, nano-actuators, and nano-processors [1]–[3]. The ability to execute in the nano-scale makes such devices very attractive in biomedical applications. However, a nano-device equipped with such nano-level components can only perform very light-weight computations, and has very limited working range [4]. On the other hand, a network of such nano-devices can cover larger area and draw inference about the sensed informations cooperatively, which is termed as a *Wireless Body Area Nano-network* (*WB2N*). It can be employed on, and/or inside a human body, for ubiquitous healthcare monitoring [5], [6]. It can also be used for smart delivery of drug, with minute precision, in order to unblock clots in the pathway of artery or released synthetic antibody for combating harmful bacteria. It is expected to form a WB2N by deploying large number of nano-devices, due to its ultra-small working range (in extreme case, it can measure pH at two different locations in the same cell [7]). The number of nano-devices varies according to the severity and type of the applications, e.g., monitoring glucose, Low-density lipoprotein (LDL) and High-density lipoprotein (HDL) molecules in bloods for diabetics, and CVD, or as cancer biomarkers for cancer treatment, or for monitoring various chronic diseases such as asthma, and osteoporosis. In this work, we envisage the design of a WB2N to be capable of energy harvesting from surrounding environment and has dual mode of communication, namely electromagnetic and molecular. Such a network is referred to in this paper as a *Green Wireless Body Area Nano-network* (*GBAN*). A GBAN is formed by enabling multi-hop communication between the source and the sink nano-devices. Further, the sensed data can be reported to a healthcare provider by means of nano-micro interface, which is assumed to be more powerful than the nano-devices.

The mode of communication in GBAN is based on the existing literature on WB2N. It is reported that the underlying communication mechanism is mainly either electromagnetic (e.g., graphene- or CNT-based nano-electronics [8]–[12]), or molecular [13]–[15]. One of the reported molecular communications is based on using engineered bacteria, where information is encoded in the DNA molecules and transmitted by bacteria-based carrier molecules [16], [17]. The advantages and limitations of both of these two communication modes are summarized in Table I. For example, electromagnetic communication offers tremendous bandwidth at the expense of higher rate of energy consumption. On the other hand, bacteria-based molecular mode provides better services in terms of bio-compatibility, and is highly energy-efficient.

We introduce in this work a novel nano-device design, in which each such device is equipped with components required for both the electromagnetic and molecular communication mechanisms. Fig. 1 shows a snapshot of two-hop communication between a transmitter and a receiver nano-device in a GBAN, where, for the sake of illustration, the communication between the sender and the relay nano-device is assumed to be molecular, whereas the communication between the relay and receiver nano-device is taken as electromagnetic communication mode. The specific mode of communication to be adopted is based on the residual energy in the nano-devices. We have assumed that such nano-devices are able to harvest energy from their surrounding environment through biomechanical-to-electrical (such as limb movements) [18], [19] or from biochemical-to-electrical (such as from glucose/O_2) [20], [21] energy conversion.

Despite having the energy harvesting capability, nano-

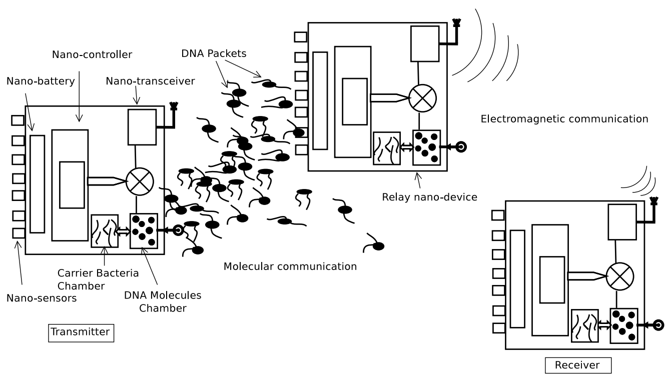


Fig. 1: A schematic view of a GBAN.

TABLE I: Comparison of electromagnetic and bacteria-based molecular communication

Approach	Advantages	Disadvantages
Molecular	1. Higher biocompatibility 2. Higher energy efficient	1. Longer delay 2. Moderate throughput
Electro-magnetic	1. Higher throughput 2. Lesser delay	1. Lesser energy efficient 2. Moderate biocompatibility

devices in GBAN may not always have sufficient energy, due to the limitations of the harvesting process, and consumption of energy for the purpose of sensing, computing, sending, and relaying information. Therefore, the energy available to a nano-device, at a particular time instant, is dependent on the rate of energy harvesting and consumption process. Due to such irregularities in the harvesting process and consumption of energy, it is imminent that some nano-devices may be overwhelmed with so much of voluminous data that it cannot process further due to its shortage of energy. Some nano-devices may be in the early stage of the energy harvesting process, so it discards the incoming data. Some may have so much limited energy content that the communication process cannot complete. So, in all cases, massive data are lost, and the energy of nano-devices is wasted. Ultimately, it poses a serious question on the realizability of such networks. This has implications on the *survivability* of a GBAN. This motivates us to explore the problem of energy management in such networks, so that a GBAN can operate for theoretically infinite time. We analyze how the energy of each nano-device can be traded in the game-theoretic framework, so that the objective of GBAN is not compromised in terms of network performance with respect to throughput and delay due to mere mismanagement of energy of nano-devices.

To the best of our knowledge this is the first work on energy management in GBAN. However, in case of general Wireless Body Area Networks (WBANs), existing works on efficient use of energy are mostly limited to the designing of routing protocols and addressing hardware level issues. Zhang et al. [22] and Olivo et al. [23] proposed chip-level power management of energy harvesting BAN node. However, network-wide energy management is broadly unaddressed in the literature. Besides, the most energy-efficient routing protocols [24], [25] considered the nodes as battery operated.

II. Problem Formulation

A. System Model

Each nano-device can be comprehended as a super-node encapsulating two vertices, where one vertex (M) denotes the molecular communication (MC), and the other (E), the electromagnetic communication (EC), as shown in Fig. 2. The edges between two super-nodes represent the type of communication between nano-devices, i.e., molecular-to-molecular and electromagnetic-to-electromagnetic.

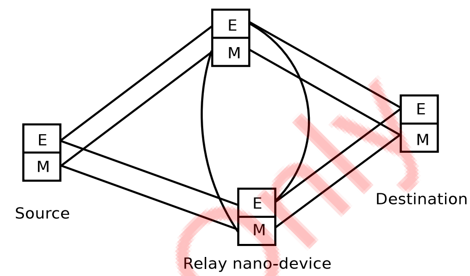


Fig. 2: Communication in GBAN.

B. Problem Formulation

As the residual energy of a nano-device does not remain constant due to factors such as temporal unavailability of the energy harvesting source, and temporal energy consumption rate of a nano-device, the goal is to manage the energy of each nano-device of GBAN such that the Quality-of-Service (QoS) in terms of network throughput, R, and network delay, D, are maintained. Let E_c, E_m, $E_{sm}(t)$, and $E_{rm}(t)$ denote the minimum energy required for communication with radio, DNA packets, and available energy at source and relay nano-devices at time instant t, respectively. The system goal can be formulated formally as follows:

$$Max\ R\ \&\ Min\ D\ \ s.t.\ \begin{cases} E_{sm}(t) + E_{rm}(t) \geqslant 2E_c \\ E_{sm}(t) + E_{rm}(t) \geqslant 2E_m \end{cases} \tag{1}$$

Since each nano-device can behave as source and potential relay of information, the expenditure of energy budget is a non-trivial issue for these devices.

III. Nash Bargaining Game and Optimal Strategy

A. Motivation

We assume that the energy states of the sender and the relay nano-devices are Poisson distributed [26], as a result of both the energy harvesting and energy consumption processes. Since the relay nano-device participates frequently in the communication process, the energy states shift to the lower ones, as shown in Fig. 3. It is evident that communication may fail if the source and relay nano-devices do not consider their energy states. So, energy management of nano-devices is crucial. We formulate the problem as a cooperative *Nash Bargaining game* [27], where each player in the game mutually benefits from reaching a certain agreement point. In GBAN, nano-devices bargain with one another in terms of their available energy, so that the QoS of the system is maintained. The Nash Bargaining Solution (NBS) provides a unique optimal agreement or operational point while enforcing fairness and efficient use of resources.

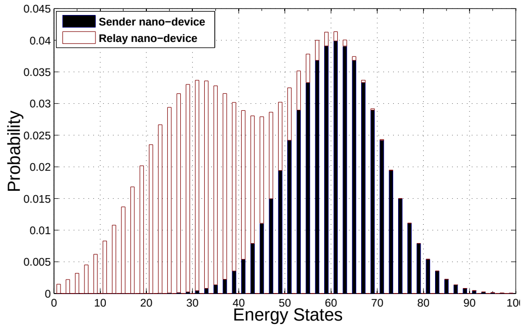


Fig. 3: Probability distribution of energy states of nano-devices. X-axis represents the energy content.

B. Energy Model

In order to reflect the temporal energy variance of nano-devices, their energy can be modeled as a Markov Process [26]. However, in our work, we adopt the model to incorporate the effect of both molecular and electromagnetic communication parameters[1], as shown in Fig. 4. The Markov model $\mathbb{X}(t)$ is defined as follows:

- *States space* $(\mathbf{S})$: Each state of $\mathbf{S} = \{s_0, s_1, s_2, ..., s_N\}$ denotes the available energy of a nano-device. The state s_0 corresponds to the situation when the available energy of a nano-device is null.
- *Transition Rule*: The transition probability from a lower energy state i to a higher energy state $i+1$, $\forall\ i \in [0, N-1]$, depends on the energy harvesting rate, P_h. The transition probability from a higher to a lower energy state depends on the communication mechanism followed by a nano-device. In case of reception or transmission of a molecular DNA packet, the transition probability is P_{MC}, where P_{MC} refers to the transmission rate of DNA packets. On the other hand, for electromagnetic communication, the transition probability from a higher energy state j to a lower energy state $j-\alpha$ is P_{EC}, where P_{EC} refers to the transmission or reception rate of radio packets. The parameter α is a constant ratio, and refers to the excess amount of energy that is needed if the packet is sent via the electromagnetic mechanism, instead of the molecular one.

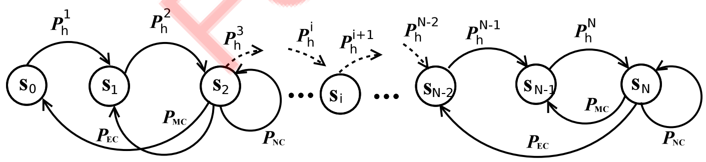


Fig. 4: Energy states of a nano-device.

C. Nash Bargaining game

We formulate the energy management problem as a two-person Bargaining game between a source and a relay nano-device. The formulation of this Bargaining game [28] is represented as a pair $(\Omega, \mathcal{D})$, and is given as follows:

$$\boldsymbol{G} \triangleq (\{\mathcal{U}_1, \mathcal{U}_2\}, \{d_1, d_2\}) \tag{2}$$

where $\mathcal{U}_1$ and $\mathcal{U}_2$ refer to the utilities of the first player (here relay nano-device) and the second player (here source nano-device), respectively, whereas d_1, d_2 are the threat points for the respective players over threat space $\mathcal{D}$. The *threat* point for each player is defined as loss in terms of utility, if they break the trading/negotiating point. The utility function for each player is defined over the strategy space $\mathcal{A} = \{EC, MC, NC\}$, where EC and MC refer to the *electromagnetic* and *molecular communication* modes, respectively, whereas NC represents the case of "No Communication", which occurs when a nano-device does not initiate communication with others due to its shortage of energy.

Each player chooses one of the available strategies with certain probabilities. The probability distribution $\mathbb{P}(X = x_i)$, where $x_i \in \{EC, MC, NC\}$, depends on the energy states and the QoS requirements of the network. One of QoS parameters in GBAN is to report delay-sensitive information to the sink. We incorporate the parameter in the utility function of the nano-device. We admit that to model a utility function incorporating different parameters simultaneously is a complex one. In fact, an accurate QoS-centric solution requires a thorough analysis of different aspects of the network protocols such as queuing delay of the packets, and the the number of retransmission attempts in case of collisions. These issues are left as work to be done in the future, in the interest of maintaining the brevity of this paper. However, a reasonably simplified model for the utility function can be obtained by taking utility value as inversely proportional to the propagation delay and directly proportional to the throughput. However, the amounts of delay and throughput vary with the mode of communication — the electromagnetic communication mode incurs lesser delay, and higher throughput than the molecular counterpart. However, a nano-device, based on its available energy, computes the probability value for choosing a particular strategy in such a way that the following equation holds:

$$P_{EC} + P_{MC} + P_{NC} = 1 \tag{3}$$

However, the procedure for assignment of probabilities is not discussed explicitly in this paper. Mathematically, $\mathcal{U}_1$ is formulated as follows:

$$\mathcal{U}_1 = p_{rd} + f_{rd}(D, R) \tag{4}$$

where p_{rd} is the probability of choosing a strategy by the relay device, which can be obtained from Equation (3). The term $f_{rd}(D, R)$ refers to the *QoS factor*, which is related to the QoS parameters, D and R, of GBAN and is discussed above. Similarly, $\mathcal{U}_2$ is given as follows:

$$\mathcal{U}_2 = p_{sd} + f_{sd}(D, R) \tag{5}$$

where p_{sd} refers to the probability of choosing a strategy by the source device, which can be computed from Equation (3). The term $f_{sd}(D, R)$ refers to the *QoS factor* corresponding to the source nano-device. The threat points d_1, d_2 are determined

[1]If GBAN is employed for orthopedic disease, then nanogenerators can convert electrical energy from when the objects are walking.

as follows:

$$d_1 = 0, \quad d_2 = 0 \tag{6}$$

D. Optimal Strategy Selection and NBS

The optimal strategy selection is done jointly by the source and relay nano-devices through mutual cooperation. The number of strategies of a source node is restricted to two – EC and MC. The strategy "NC" is not applicable, because if the source nano-device has no available energy, it does not initiate communication. However, a relay nano-device has option for choosing any one of the three strategies. It is important to note that a relay nano-device may not choose EC mode for relaying data even if it possesses sufficient energy. It is due to the fact that the relay device, at that moment, may have its critical data in the queue to send, thereby averting the risk of depletion of its energy by not choosing the EC mode.

The NBS provides optimal utilities (U_1^*, U_2^*) for both players such that they are unable to get additional utilities, if they deviate from the negotiation point. The NBS is obtained by solving the following *optimization* problem [27]:

$$\underset{\mathcal{U}_1,\mathcal{U}_2}{\operatorname{argmax}}(\mathcal{U}_1 - d_1)(\mathcal{U}_2 - d_2), \ s.t. \ (\mathcal{U}_1, \mathcal{U}_2) \geqslant (d_1, d_2) \tag{7}$$

In general, NBS can be reduced to solving a convex optimization problem. The complexity of the algorithm for the solution of such a problem depends on the number of unknown variables (n), and the constraints, and the cost of evaluating derivatives of the constraint functions. The complexity is in order of $O(n^r)$, where $r \geqslant 3$ [29]. However, in GBAN, we have a two-player Bargaining game with three strategies. So, the computation of deriving the solution reduces to constant time. The energy consumed by the game strategy used in GBAN is fixed and is very less (typically, less than a pico-joule).

E. Example

We present an illustrative example of the Bargaining game between the source and relay nano-devices. The payoff matrix is presented in Table II. Interestingly, it can be observed that the payoff matrix is diagonal, because both the source and relay nano-devices can communicate using either EC or the MC mode. Therefore, the solution strategy is to use EC, as it gives optimal utilities for both the players.

TABLE II: Example of Bargaining game

		Player 1 (Relay nano-device)		
		EC	MC	NC
Player 2 (Source nano-device)	EC	0.8,0.6	0,0	0,0
	MC	0,0	0.2,0.3	0,0
	NC	0,0	0,0	0,0.1

F. Distributed algorithm for selection of optimal strategy

The source nano-device, based on the current energy state and energy harvesting rate, computes a payoff vector V for each chosen action in order to forward data. It tags the vector V with the *initialization* packet, and broadcasts it to find a potential relay nano-node.

After decoding the *initialization* packet, a relay-node forms a payoff matrix $(M_{i,j})_{3\times3}$ by including its own payoff value. Then, it derives a Nash solution strategy. The negotiated strategy is sent to the source nano-device, which, on the other hand, selects the strategy of corresponding to the highest utility value among those which are received from potential neighbors. The psuedo-code is presented in Algorithm 1.

Algorithm 1: Selection of optimal strategy.

Data: Source's payoff vector V including energy states
Result: Optimal strategy set $(\mathcal{A}_1, \mathcal{A}_2)$
$E \leftarrow$ current available energy of the relay nano-device;
$\epsilon \leftarrow$ predefined minimum energy value of the relay;
if $E > \epsilon$ **then**
  Calculate its own Payoff vector V;
  Construct the Payoff matrix $(M_{i,j})_{3\times3}$;
  Find the NBS for optimal strategy for both nano-devices;
  Share it with the source nano-device;
else
  Abort the procedure;
end

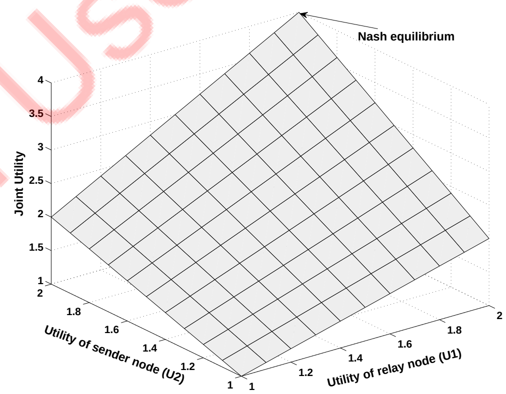


Fig. 5: Nash equilibrium for the proposed bargaining game.

G. Existence and Uniqueness of Nash equilibrium

To prove that the proposed Bargaining game $\boldsymbol{G}$ between the source and the relay nano-devices has unique solution, it is required to satisfy the following four axioms [27]:

1) *Pareto optimality*: Denotes the strategy profile S^* such that no player gets higher utility without reducing the utility values of the others. Mathematically, it is written as follows:

$$u(s_i^*, s_{-i}^*) \geqslant u(s_i, s_{-i}), \forall \ players \ i \in N$$

2) *Invariance to equivalent utility representation*: Refers to the invariant nature of the Bargaining game, despite the *affine transformation* of utilities of all players. The transformation is as follows:

$$u(s_i) = \alpha u(s_i) + \beta, \quad where \quad \alpha \geqslant 0.$$

3) *Independence of irrelevant alternatives*: If a subset $S' \subseteq S$ consists the solution of the game, another game (had we formulated one) within S' also produces the same solution.

4) *Symmetry*: The utility values of each player is symmetric with respect to $(u_i, u_{-i}) = (u_j, u_{-j})$, i.e., the players are interchangeable in the payoff matrix.

The proposed Bargaining game satisfies the axioms given above. The joint strategy set $\mathcal{S} \in \{\mathcal{U}_1, \mathcal{U}_2\}$ has a pareto optimal solution, since $\mathcal{U}_1$, and $\mathcal{U}_2$ increase according to their probability values. This is shown in Fig. 5. It is obvious that axioms (2) and (3) are also satisfied. If we examine the payoff matrices of two players, the game is not symmetric. However, Kalai [30] showed that a non-symmetric Bargaining game also has a unique solution. We conclude that the proposed game has an NBS.

IV. Analysis

A. Network delay

In order to estimate a closed-form expression for *network delay* (D), we introduce the terms p^e and p^m, which refer to the probabilities of tuning with the respective EC-to-EC and MC-to-MC modes between the source and relay nano-devices, respectively. The delay incurred by the EC mode (D^{elc}) is given as follows:

$$D^{elc} = p^e \times \sum_{i=0}^{k} (T_p^e + T_d^e + iT_o) \tag{8}$$

where T_p^e, K, T_d^e refer to propagation delay for EC mode, number of retransmissions, and radio packet transmission time, respectively. T_o refers to the time-out value, which can be computed from the underlying MAC, channel condition, and receiver's packet drop probability. The delay incurred by the MC mode (D^{mol}) is given below:

$$D^{mol} = p^m \times \sum_{j=0}^{L} (T_p^m + T_d^m + jT_o) \tag{9}$$

where T_p^m, L and T_d^m refer to the delay of propagation, number of retransmissions, and packet transmission time for molecular communication. It may be noted that the following inequality holds in the proposed network architecture:

$$T_p^m > T_p^e \tag{10}$$

To capture the delay occurring from the mismatch of communication modes between the source and relay nano-devices, we define the term p^{mt} as the probability of *mistuning* between two communicating nano-devices. Therefore, the delay due to mistuning, D^{mis}, is computed as follows:

$$D^{mis} = p^{mt} \times \left(\frac{T_p^e + T_p^m}{2} + \frac{T_d^e + T_d^m}{2} \right) \tag{11}$$

Finally, from Equations (8), (9), and (11), we have

$$\begin{aligned} D = L_h \times ((1 - p^{mt})p^e \times \sum_{i=0}^{k} (T_p^e + T_d^e + iT_o) + p^m (1 - p^{mt}) \\ \times \sum_{j=0}^{L} (T_p^m + T_d^m + jT_o) + p^{mt} \times (\frac{T_p^e + T_p^m}{2} + \frac{T_d^e + T_d^m}{2}) \\ + T_s \times N) \end{aligned} \tag{12}$$

where L_h is the total number of hops in a communication chain, and T_s is the delay incurred in switching between two communication modes.

B. Network throughput

In GBAN, throughput is computed as follows:

$$R = \frac{M_r \times P_{st}}{D} \tag{13}$$

where P_{st} refers to the probability of successful packet transmission between the source and destination nodes, and M_r is the total number of information bits.

C. Probability of mistuning

Let $\mathcal{A}$ and $\mathcal{B}$ be two sets consisting of tuples $(x, p_{\mathcal{A}}(x))$ and $(x, p_{\mathcal{B}}(x))$ defined over the energy state x, $\forall x \in \mathbf{S}$. The second component of the tuples refers to the probability of being in a energy state x. The sets $\mathcal{A}$ and $\mathcal{B}$ are assumed to denote the sender and relay nano-devices, respectively. The *matching* set, $\mathcal{M}$, is defined as follows:

$$\begin{aligned} \mathcal{M} = \{(x, p(x)) : p_{\mathcal{A}}(x), p_{\mathcal{B}}(x) \geqslant \theta \text{ and} \\ p(x) = min\{p_{\mathcal{A}}(x), p_{\mathcal{B}}(x)\}\} \end{aligned} \tag{14}$$

where θ is a predefined constant, and is related to the minimum energy of a nano-device required for communication. Hence, p^{mt} can be obtained as follows:

$$p^{mt} = 1 - \frac{|\mathcal{M}|}{|\mathbf{S}|} \tag{15}$$

where $|.|$ is the cardinality of a set.

Theorem 1. *The matching set $\mathcal{M}$ is a convex set.*

Proof. As we have already shown, the utility space of each player is convex, since the function associated with utility is linear. Further, $\mathcal{M}$ contains the energy states based on which the players form their strategy spaces and the optimal strategy can be obtained from it. Therefore, $\mathcal{M}$ is a convex set. □

D. Rate of change of residual energy of a nano-device

Let E be the total energy of a nano-device at a particular time instant t, which is a function of following parameters:

$$E = f(e(t), m(t), h(t)) \tag{16}$$

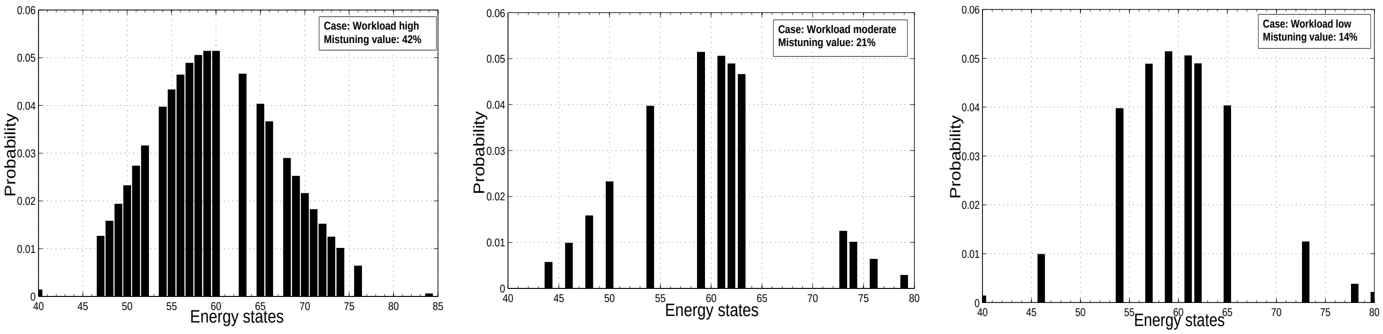
where $e(t)$, $m(t)$ denote the energy consumed for electromagnetic and molecular communications, respectively, and $h(t)$ refers to the energy harvested by means of a harvesting process. The rate of energy consumption is defined as follows:

$$\frac{dE}{dt} = \frac{\partial E}{\partial e}.\frac{\partial e}{\partial t} + \frac{\partial E}{\partial m}.\frac{\partial m}{\partial t} + \frac{\partial E}{\partial h}.\frac{\partial h}{\partial t} \tag{17}$$

As previously discussed, we can write $\frac{\partial E}{\partial m} = \eta.\frac{\partial E}{\partial e}$, where $\eta \in (0, 1)$ is a constant. So, Equation (17) reduces to

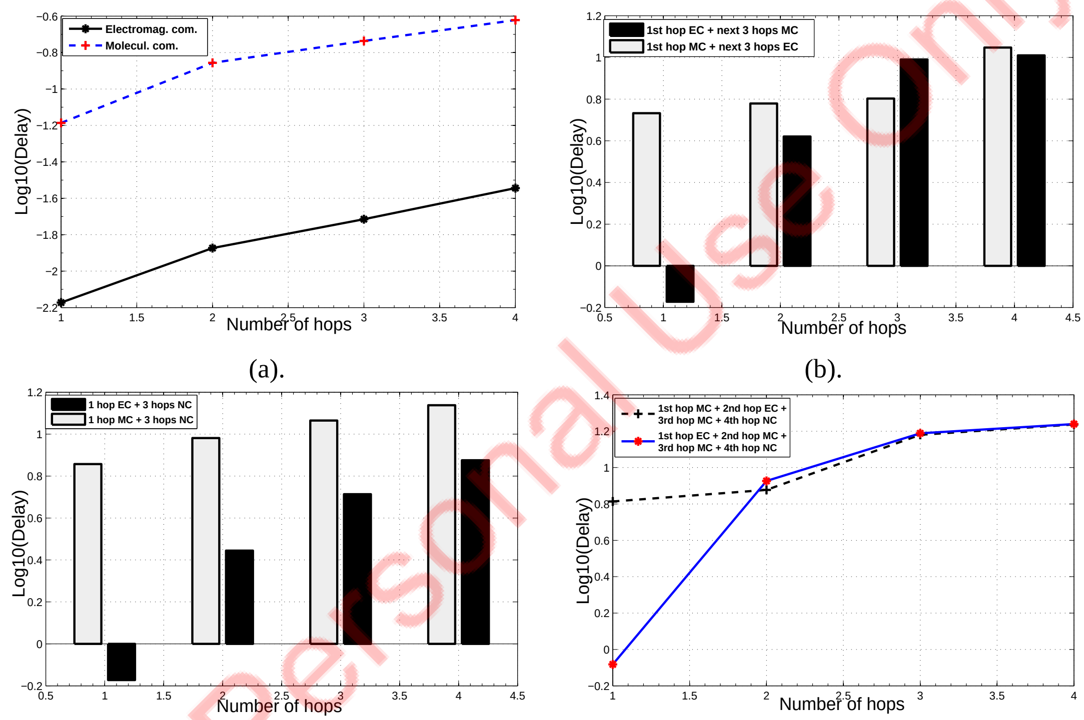
$$\begin{aligned} \frac{dE}{dt} &= \frac{\partial E}{\partial e}.\frac{\partial e}{\partial t} + \eta.\frac{\partial E}{\partial e}.\frac{\partial m}{\partial t} + \frac{\partial E}{\partial h}.\frac{\partial h}{\partial t} \\ &= \frac{\partial E}{\partial e}.(\frac{\partial e}{\partial t} + \eta.\frac{\partial m}{\partial t}) + \frac{\partial E}{\partial h}.\frac{\partial h}{\partial t} \end{aligned} \tag{18}$$

$\frac{\partial e}{\partial t}$ and $\frac{\partial m}{\partial t}$ are the rates of energy consumption due to EC and MC, respectively, and can be obtained from real experimentation. Based upon the obtained values, Equation (18) can



(a) High workload at relay node (b) Moderate workload at the relay node (c) Low workload at the relay node

Fig. 6: Probability of mistuning for High, Moderate, Low workloads.



(a). (b). (c). (d).

Fig. 7: The legends in sub-figures show delays corresponding to the different combinations of EC, MC, and NC.

be solved for the expression of E. The term $(\frac{\partial e}{\partial t} + \eta.\frac{\partial m}{\partial t})$ is important in determining the energy profile of a nano-device. Further, the following inequalities hold:

$$\frac{\partial E}{\partial e} \leqslant 0 \quad and \quad \frac{\partial E}{\partial h} \geqslant 0 \tag{19}$$

Theorem 2. *There exists at least one point in the energy profile of each nano-device in a communication chain profile, for which* $\frac{dE}{dt}$*=0.*

Proof. Let us consider the case when the rate of energy consumption $\frac{dE}{dt} < 0$. This condition occurs when the rate of energy consumption due to either mode exceeds the rate of energy harvesting process. It may be noted that the locus of $\frac{dE}{dt}$ is linearly bounded in the worst case. If $\frac{dE}{dt}$ of a nano-device follows a linear curve, the nano-device will not participate in the communication chain, since either the energy harvesting process of the node remains off, or the energy consumption of the nano-device is so high that the harvested energy has no effect on the energy profile of the nano-device. Therefore, there exists at least one point in the curve, such that $\frac{dE}{dt} = 0$. Further, if $\frac{dE}{dt} > 0$, then the rate of energy harvesting is greater than the rate of energy consumption. Since we assumed that energy harvesting is an intermittent process, $\frac{dE}{dt}$ does not behave as a *strictly monotonically increasing function*. Thus, there exists at least one point such that $\frac{dE}{dt} = 0$. □

Theorem 2 has implications on successful data delivery in GBAN. It indicates that there exists an equilibrium point in each nano-device in the communication chain. The equilibrium point dictates each nano-device to take the decision of

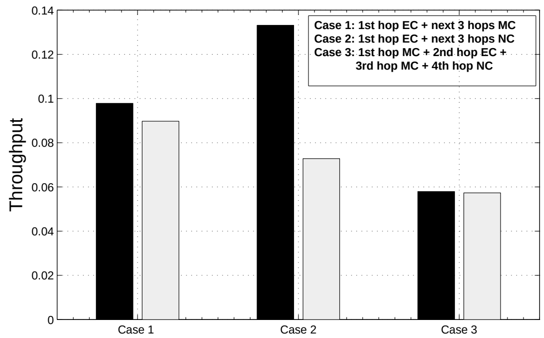


Fig. 8: Throughput for combinations of EC, MC, and NC.

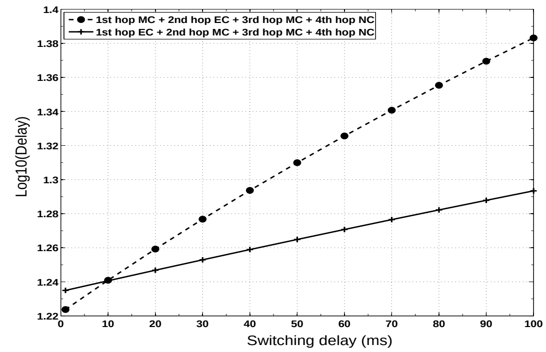


Fig. 9: The effect of switching delay for two different orders of EC, MC, and NC.

choosing a particular mode of communication, EC or MC.

E. Experimental Design

We used MATLAB for evaluating the performance of the proposed solution. In the evaluation framework, the nodes were distributed uniformly. The communication range for both modes, EC and MC, was assumed to be 10 mm, and maximum 4-hop communication was considered. The packet delays for EC and MC modes, and switching between modes were taken as 40 milliseconds, 2 seconds, and 0.8 milliseconds, whereas the energy capacity of each nano-node was taken as 800 pico-joule.

The analysis of mistuning between the sender and the relay nano-devices was performed, where the parameters were taken based on the probability values of a node to be in specific energy states. The observation was made by keeping the source nano-device fixed in particular probability distribution of energy states, whereas the relay nano-device was configured to adopt several probability distributions of energy states based on the following workloads:

1) *High workload*: Occurs when the relay nano-device transmits own data and forwards the neighbor's data, thereby pushing towards lower energy states.
2) *Moderate workload*: When energy consumption is not sufficiently high or low.
3) *Low workload*: The probability of occupying high energy states due to low energy consumption.

F. Results

Fig. 6 shows that the probability of mistuning between the source and relay nano-devices decreases upto 42%. Even if both nano-devices are in the high energy states, the value of mistuning is comparable to that of the case of moderate workload. This is because no coordination between the source and relay nodes is established for communication. So, the cooperative NBS is a candidate strategy for improved coordination among temporal energy-fluctuated nano-devices in maintaining network performance.

Figs. 7 and 8 show the network delay and throughput based on different values of p^{mt}, p^{e}, and p^{m}. It is observed that the more are occurrences of molecular communication mode in the communication chain, the longer are delays experienced by data packets. It is interesting to note that the switching delay may not be a crucial factor (although we assumed that the value of switching time is very less), if the end-to-end communication path encounters more electromagnetic modes of operation. However, the effect of variation of switching delay is observed as shown in Fig. 9. The increasing switching delay causes longer network delay for alternate switching between EC and MC modes than the same number of EC and MC modes with few switching in a communication chain.

G. Limitations

We observed that the sequence between MC, EC, and NC in the communication chain has no significant effect on the overall network delay and throughput performance. The reason is that we assume that the switching delay is constant, and has relatively very less value. Further, we did not consider the *relaxation time* or *recovery time* to influence the diminishing molecular noise occurring due to electromagnetic communication.

V. Conclusions

In this paper, we present a novel GBAN architecture, where each node is capable of communicating in both the molecular and electromagnetic modes, for better network QoS performance and improved ubiquity in healthcare services. The energy harvesting capability of each node prolongs a network's lifetime. However, the intermittent nature of the energy harvesting process poses the challenging problem of energy management between nano-devices for maintaining QoS requirement. In our work, we formulate the problem in light of a Nash Bargaining game. The optimal strategy obtained from the Nash equilibrium solution indicates significant improvement in network throughput and delay.

Currently, nano-devices equipped with energy harvesting capabilities are under development. So, the modeling and verification of energy harvesting and consumption process of a nano-device is somewhat difficult. For our present work, we assume a probabilistic model for the determination of payoffs. However, in our future works, we intend to explore a better and accurate model. Nevertheless, our work on energy management among nano-devices is expected to set the ball rolling for future research on the development of novel GBANs. In the future, we plan to study other aspects of energy management in these networks.

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