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NetADD: Network Flow Based Distributed Topology Control on Addressing Asymmetric Data Delivery in Nanonetworks

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***Abstract*—Architecting nanonetwork-based Coronary Heart-Disease (CHD) monitoring requires a set of nanodevice-embedded drug eluting stents (nanoDESs) inserted inside the affected sites of coronary arteries of the heart to cooperatively collect medical information therein, and transmit the information via the nano-macro interface (NM), which is inserted into the intercostal space of the rib cage. These nanonetworks, which operate in the terahertz band (0.1 – 10 Thz), face increased complexity in delivering data of underlying nanonetworks to the NM, due to the limited energy content of nanoDESs. In this work, we propose a distributed topology control algorithm based on the solution of well-known *Network flow problem* for addressing Asymmetric Data Delivery (NetADD). The generated topology is dynamic in the sense that it changes according to the energy levels of the nanoDESs. The proposed algorithm helps establish the topology and balance the load on nanoDESs. The proposed approach changes the topology if there arises a need to balance the energy content of the nanoDESs. We study the problem of asymmetric data delivery in various types of network topologies as well. The proposed solution is shown via extensive simulation to yield improved performance over the existing topology control solutions with respect to data delivery ratio, energy consumption, delay, and the events of shutdown.**

***Index Terms*—Asymmetric data delivery, coronary heart disease, coronary-stent placement, network max-flow, load balance, distributed topology control**

I. Introduction

CHD is one of the most common causes of death in the world [1], [2]. In CHD, a waxy substance called plaque builds up inside the coronary arteries, which are responsible for supplying oxygen-rich blood to our heart muscles. Plaque build-up inside the artery decreases the cross-section and makes the artery narrow, thereby resulting in abnormal blood flow. This abnormal flow may cause chest pain, heart attack, or even death.

In this paper, we propose a novel algorithm for distributed topology control using network flow in Wireless Nanosensor Networks (WNSNs) [3] for CHD monitoring. Each of the nanosensor nodes deployed for monitoring CHD consists of a sensing unit, an actuation unit, a nano-transceiver unit, a processing unit, a storage unit, and a nano-battery located inside coronary arteries. A nanosensor node senses the event occurrence in coronary arteries and sends the information to the NM, which is located inside the intercostal space of rib cage. The NM connects to the Internet and gets the command to release drug, if required. It works as a gateway for all nanoDESs. Nano-sensor networks work in the terahertz band, with communication ranges of the nodes in the few tens of milimeters (mm) order. Due to the small sensing and communication ranges of sensor nodes, multiple nanoDESs need to be deployed inside coronary arteries, which sense and send information to the NM. The power level of a nano-battery power is in the picojoule (pJ) range, and it is harvested from vibration motions of the materials by leveraging the property of piezoelectricity of the material. The small amount of harvested energy should be used in an optimal manner, so that information from all sensor nodes can be received properly, while improving the lifetime of the network.

To optimize energy efficiency, instead of sending packets directly to the NM, nanoDESs can send them through multiple hops. This enables the nanoDESs at long distance to be stable, because if the nanoDESs at such distance send their packets directly, then relatively large amount of energy will be required and those nanoDES go into shutdown phase. The main idea behind the proposed multi-hop distributed topology control algorithm is based on the solution of the well-known graph-theoretic problem *network flow*. The resulting network topology is generated by exploiting the solution of the network flow problem. The main *contributions* of this work are as follows:

- Mapping the topology control into network flow problem,
- Proposing a novel algorithm for balanced distributed topology control, and
- Providing analysis for energy-stable topology.

The rest of paper is organized as follows. Section II describes the related work. The approach to convert the topology control problem to the network max-flow problem is given in Section III. Section IV outlines the data delivery in different types of network topology. Section V elaborates the main design of the distributed topology control protocol. We describe the concept of energy-wise stable topology in Section VI. Section VII presents results, while Section VIII concludes the work.

II. Related Work

On intra-body nanocommmunication, Akyildiz et al. [4] explained the novel challenges and safe techniques for developing Internet of bio-nanothings and introduced this paradigm concept for communication and networking in the biomedical domain. Toward developing the fundamentas of intra-body communication, Guo et al. [5] developed channel model for optical communication among nano-sensors, calculated the total path loss by considering absorption loss and molecular loss, and found out that the scattering loss is more than absorption loss in the case of optical frequencies. On the other hand, Misra et al. [3] introduced an architecture of green wireless body area networks, where nanodevices harvested energy from their surrounding environment and increased their lifetime. in the case of terrestrial wireless sensor networks, Han et al. [6] explained various algorithm design for energy-efficient data communication. Furthermore, De Couto et al. [7] designed a high throughput path metric for multi-hop wireless routing. To increase data delivery and decrease the delay of packet delivery, Gu and He [8] introduced energy-efficient, dynamic switching algorithms.

On nanonetworks-based CHD monitoring, the ”Catch the Pendulum” (CAP) algorithm [9] focused on periodic change in mean distances among nanoDESs and the NM. In case, when the distance between a nanoDESs and the NM is minimum, communication takes place, since the energy required is directly proportional to the square of distance. When the communication takes place at the minimum distance, energy consumption is less, making it an optimal approach for communication. However in CAP, the star topology is considered, because of which the nanoDESs situated at relatively farther distances require relatively higher amount of energy. CAP is unable to handle the problem of transitioning to the “shutdown” of a nanoDES. On the other hand, regarding topology-control energy-efficient data dissemination in traditional wireless sensor networks, Pan et al. [10] proposed a topology of sensor networks by classifying application node (AN) and base station (BS) based on computational geometry. The authors derived the optimal position of BS with respect to ANs in a two-tiered wireless sensor networks. Furthermore, Olfati-Saber and Murray [11] discussed the consensus problems for directed networks with fixed and switching topologies. However, our work focuses on improving the efficiency of data delivery as well as shutdown events in the case of asymmetric data delivery for CHD monitoring.

III. Problem Formulation

A. System model

For CHD monitoring, nanoDESs are deployed inside the heart. The nanoDESs harvest energy from the surrounding environment at a very slow rate. This constraint mandates optimal energy utilization. The existing techniques for optimizing energy utlization are unsuitable for use because nanoDESs transitions to the shutdown states for some time intervals, which decreases the data delivery ratio. Consequently, the use of such an approach for CHD monitoring is not desirable. Hence, to reduce the chance of shutdown, and to increase the data delivery ratio, we designed a dynamic distributed topology control protocol. In this protocol, the topology is decided by the status of the rate of energy harvesting and the rate of consumption of transmission. The status information of these are exchanged by message passing. After some time interval, if the status of a nanoDES changes, the topology also changes accordingly.

The network topology consists of nanoDESs and a NM. NanoDESs sense the event and send the sensed information to the NM. The NM works as the gateway and sends this information to the Internet. The nanoDESs are programmed to emit drug if instructed from the NM. The NM communicates at both the nano and macro scales, as it is assumed to have the required transceiver circuits for communication in both the THz and RF bands. NanoDEss harvest energy from oscillatory deformation of heart by exploiting the piezoelectric effect of the nanowires, caused by the deformed force. All other nanoDESs in range of a specific nanoDES are said to be connected to this nanoDES. The connection of all nanoDESs and the NM results in the desired topology for CHD monitoring. This natural topology may not satisfy the data flow constraints of each link, thereby necessitating the reconfiguration of the topology and adjusting the loads across the links. The topology control algorithm with load balancing is described in Section V.

B. Mapping topology control to network flow problem

Due to the varied intensities of energy harvesting and the available energy contents of the nanoDESs at any particular time instant, the data flow capacity of each link varies. With these information, the initial topology of this nanonetwork can be modeled as a graph $G = (V, E)$, where V refers to the set of nanoDESs and $(u, v) \in E$ to the set of the edges (or links). The capacity $c(u, v)$ of a link (u, v) denotes the limit of packets that can be supported by the link between two nanoDESs. Let the source and the sink be denoted as S and T, respectively. A flow in the graph G is defined as a real-valued function $f : V \times V \to \mathbb{R}$, which satisfies two basic properties:

- *Capacity constraint*:
$$\leq f(u, v) \leq c(u, v),\ \forall u, v \in V$$
- *Flow conservation*:
$$\sum_{v \in V} (p_{in})_v = \sum_{v \in V} (p_{out})_v\ ,\ \forall v \in V\text{-}\{S, T\},$$

where $(p_{in})_v$ is the number of incoming packets and $(p_{out})_v$ is the number of outgoing packets at each nanoDES v. In the initial graph consisting many links between the nanoDESs and the NM, the problem of topology control is to find out an efficient topology with reduced links, where the flow in terms of total number of packets transmitted to the NM is to be maximized. Eventually, this problem is a network flow problem, which can be solved using *max-flow* algorithm [1]. The resulting links provided in the solution is the required topology.

C. Edge capacity

Edge capacity refers to the maximum number of packets that can be sent through an edge. It is assigned on the basis of the transmission and harvesting energy. The transmission energy is calculated by using the formula of total path loss, L^{tl}, formula for inta-body channel modeling for THz band, and is given as follows [12]

$$L^{tl}(f) = L^{sp}(f) \times L^{ab}(f) \times L^{sc}(f), \tag{1}$$

[1] The max-flow algorithm is provided in supplementary materials

where $L^{sp}(f)$, $L^{ab}(f)$, and $L^{sc}(f)$ are the spreading loss factor, the molecular absorption factor, and the scattering loss factor, respectively. At this juncture, it is noted that the scattering loss factor due to scattering from molecules in intrabody channel is not considered, since in terahetz channel the value of scattering loss is negligible [12]. The spreading loss factor due to the spreading of the propagating at a distance d is given by

$$L^{sp}(f) = D\left(\frac{\lambda_g}{4\pi d}\right)^2, \quad (2)$$

where λ_g refers to effective wavelength and is equal to λ/n', n' and n'' denote the real and complex parts of refractive index n of a material, respectively. Whereas D represents the directivity of the nanoantenna. On the other hand, based on Beer-Lambert law, the molecular absorption loss factor due to the attentuation caused by molecular absorption of the constituent molecules of the propagating medium is calculated by using [12]

$$L^{ab}(f) = e^{-\mu_{abs}d}, \quad (3)$$

where μ_{abs} is the molecular absorption coefficient and related with refractive index of the material, given as follows

$$\mu_{abs} = \frac{4\pi(n'')}{\lambda_g}. \quad (4)$$

The harvesting energy is calculated using the equation given in [13]. The rate of harvesting energy depends on the current energy. For a specific current energy value, the harvested energy is maximum for a given time quantum. The time quantum refers to the duration after which the nanoDES again gets the chance to send data based on the adopted multiple access scheme, such as time division of multiple access (TDMA). If E_{curr} denotes the current energy level of nano-battery and E_{max} maximum possible charge, the number of cycles required to charge [13] from E_{curr} to E_{max} is

$$N = \left\lceil -\frac{VC}{Q} log\left(1 - \sqrt[2]{\frac{E}{E_{max}}}\right)\right\rceil \quad (5)$$

where E is the harvested energy to charge up to E_{max}

$$E = E_{max} - E_{curr} \quad (6)$$

In Equations (5) and (6), V denotes the voltage of capacitor, C the capacitance of the capacitor, and Q is the charge produced in one cycle. If t_{cycle} denotes the time period of one cycle, then the total time required to charge from E_{curr} to E_{max} is T_{max}, which is given by

$$T_{max} = N \times t_{cycle} \quad (7)$$

The harvesting rate

$$\begin{aligned} h &= \frac{E}{T_{max}} \\ &= \frac{E}{N \times t_{cycle}} \\ &= \frac{E}{-\frac{VC}{Q} log\left(1 - \sqrt[2]{\frac{E}{E_{max}}}\right) \times t_{cycle}} \end{aligned}$$

Therefore,

$$h = -k\frac{E}{log\left(1 - \sqrt[2]{\frac{E}{E_{max}}}\right)} \quad (8)$$

where k is a constant and $k = \frac{Q}{VCt_{cycle}}$.

IV. Data Delivery in Nanoscale communication Networks

A. Data delivery in star topology

In the star topology of nanonetworks, each of the nanoDESs sends its data to the NM directly and is unaware of the existence of other nanoDESs. The nanoDESs, which are situated at larger distance from the NM require more energy to deliver their packets and thus transition to the shutdown phases after some time while involved in sending continuous packets. After recharging their batteries, they resume sending their packets. Hence the total data delivery of the network is reduced in the star topology.

B. Data delivery in distributed topology

In distributed topology, the weight of a link is defined by the number of packets transmitted per unit time. The limit of packets to be delivered is decided by the amount of harvesting energy of the source and the transmission energy required to send the packets through the links to next nodes. Since all the links have packet limits, the paths of the distributed topology determined by using NetADD protocol (described in Section V) utilize the limits so that all the nanoDESs are in stable states in which the required transmission energy of each nanoDES is not higher than the harvesting energy.

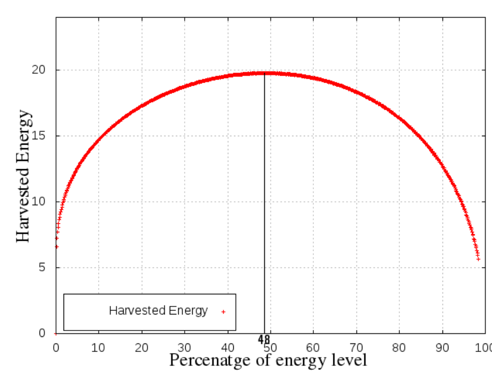


Fig. 1: Harvested energy

V. NetADD: The Proposed Protocol

A. Initial setup

During the initilization phase, each of the nanoDESs sends its control packets to the NM directly in order to estimate the budget of energy consumption for sending data packets to the NM. The nanoDESs, which are situated at far distance more than a few centimeters away from the NM, according to the formula of total path loss, require more energy to send their packets. So, their energy levels decrease at faster rate. After certain interval of time engaging in data delivery, these nanoDESs might end up to the shutdown states and are unable to send further data packets. This phenomenon emerges because of their rates of harvesting energy are lesser than the rates of transmission energy. However, the nanoDESs, which are situated nearer the NM lose lesser amount of energy, making them continue sending packets. Based on the difference in the rates of harvesting and transmission energy, the nanoDESs are classified into two sets – (a) *Potential Relay-cum-Source nanoDES* (PRN), and (b) *Source nanoDES*, as shown in Fig. 2. The following are the lists of characteristics

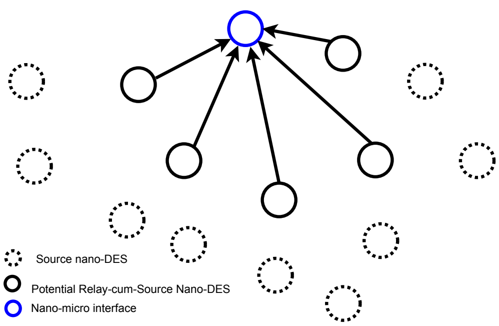


Fig. 2: Classification of Potential Relay-cum-Source nanoDESs (PRNs) and source nanoDESs

of PRNs and nanoDEs:

- *Characteristics of a source nanoDES:*
  1) A nanoDES, whose maximum harvesting energy is lesser than its transmission energy.
  2) It is not directly connected to the NM and use PRN(s) to send its packet to the NM.
- *Characteristics of a PRN:*
  1) A source nanoDES, whose maximum harvesting energy is higher than the transmission energy.
  2) It is directly connected to the NM.
  3) It is able to send its own packet and it may act as relay for other source nanoDESs.

B. Establish Distributed Topology

As nanoDESs are initially not aware of their neighbors, their neighbors should be discovered at the earliest. The neighbors are discovered by either a source nanoDES using broadcasting packets to find its potential neighbors or by a PRN using broadcasting packets to inform the source nanoDES that the PRN could be a potential neighbor. After broadcasting the packets, the source nanoDES waits for the acknowledgements from the potentials neighbors and establishes connection with them, thereby leading to the formation of a connected network topology. In this topology, the PRNs are connected to the NM and the source nanoDES is connected to its potential neighbors. No connectivity may exist between two PRNs.

Source nanoDESs send their packets through the PRNs. The PRNs may have to send more packets than their capability. So the load on PRNs should be balanced. To balance the load, Algorithm 1 (psuedo codes of the algorithm as well as relevant subroutines are given in the supplementary materials), uses the subroutine *load balance*, which implements different multiple cases, such as : (1) If the total number of incoming packets equals the total possible number of transmission packets; (2) If the total number of incoming packets is less than the total number of outgoing packets; and (3) If the total number of incoming packets at any nanoDES is greater than the total possible number of outgoing packets. After the loads at each link, each nanoDES, and each PRN of the network are balanced, Algorithm 1 calls the subroutine *max flow* to find out the paths that are used to send the packets to the NM. The paths eventually form the energy-efficient topology. For the sake of better understanding of the procedure of the establishment of the distributed topology, we illustrate it with an example, which is provided in the supplementary materials[2].

VI. Stable topology

A topology is said to be energy-wise stable if the probability of shutdown of each nanoDES is equal to zero, while using maximum possible packet limit of each edge. It is possible to have the situation where the transmission energy rate is less than or equal to the harvesting energy rate for all nanoDESs. The following may occur due to harvesting and transmission:

- *Case I:* When $T_r = h$
  In this case, δE = 0, where δE is change in energy level of nano-battery, and T_r is transmission rate. In this case, the nanoDESs do not transition to the shutdown phase. In a particular time quantum, the amount of energy required will be produced in that specific time quantum. If h_{max} denotes the maximum harvesting rate, h_p is the harvested rate at the saturation point. We have

$$T_r = h = h_p \leq h_{max} \quad \text{when } .48E_{max} \leq E_{curr} \leq E_{max} \tag{9}$$

- *Case II:* $T_r > h$
  In this case, $\delta E < 0$, E_{curr} decreases from E_{max} and h increases (see Fig. 1). From E_{max} to $.48E_{max}$ there must be a saturation point (where $T_r = h$) If energy is used, the load is balanced. If h_p is the harvested rate at the saturation point, we have

$$h < T_r \leq h_p \leq h_{max} \quad \text{when } .48E_{max} \leq E_{curr} \leq E_{max} \tag{10}$$

- *Case III:* When $T_r < h$
  In this case, $\delta E > 0$. From E_{curr}, E_{max} increases, and h decreases (refer to Fig. 1). From E_{curr} to E_{max}, there must be a saturation point (where $T_r = h$). If the load on nanoDES is balanced, we have,

$$T_r \leq h_p \leq h_{max} \quad \text{when } .48E_{max} \leq E_{curr} \leq E_{max} \tag{11}$$

From Cases I, II, and III, the common condition for ensuring energy-wise stability is $T_r \leq h_{max}$. This is a sufficient condition for energy-wise stability of a nanoDES. If all nanoDESs satisfy this condition, then the topology is energy-wise stable.

Proposition 1. *The maximum rate of harvesting energy (h_{max}) for a nano-battery is achieved when $E_{curr} = .48E_{max}$, where E_{curr} is the current energy level and E_{max}*

[2]Due to the constraint of the page limitation

is maximum energy level of a nano-battery.

Proof. We observe that the harvesting rate equation (Equation 8) depends on the harvested energy E, which depends on E_{curr} from Equation 6. So, there must be a value of E_{curr} for which harvesting rate is maximum. We differentiate the Equation 8 to find the critical point and find out the maxima relative to E.

Differentiating both side in eqn 8 with respect to E, we have,

$$\frac{dh}{dE} = -\frac{k}{log\left(1-\sqrt[2]{\frac{E}{E_{max}}}\right)} - \frac{kE}{\left(1-\sqrt{\frac{E}{E_{max}}}\right)\left(log\left(1-\sqrt[2]{\frac{E}{E_{max}}}\right)\right)^2}\left(0-\frac{1}{2\sqrt{EE_{max}}}\right)$$

For finding critical points, $\frac{dh}{dE} = 0$. We have,

$$0 = -\frac{k}{log\left(1-\sqrt[2]{\frac{E}{E_{max}}}\right)} + \frac{kE}{2\sqrt{EE_{max}}\left(1-\sqrt{\frac{E}{E_{max}}}\right)\left(log\left(1-\sqrt{\frac{E}{E_{max}}}\right)\right)^2}$$

Solving the above equation and substituting the value of E from Equation 6, we have,

$$2\left(\sqrt{\frac{E_{max}}{E_{max}-E_{curr}}}-1\right)log\left(1-\sqrt{\frac{E_{max}-E_{curr}}{E_{max}}}\right) = 1 \tag{12}$$

Finally, we get Equation 12, which is a such an equation that is difficult to solve analytically. We use simulation to solve this equation. For different values of E_{curr}, the harvested energy (H) within a time quantum is different. With the increase of E_{curr}, the value of H increases and reaches its maximum value. Thereafter, with increase in the value of E_{curr}, the value of H decreases and reaches a minimum value.

After testing the formula for different inputs of E_{curr}, it is seen that when E_{curr} is 48% of E_{max}, then harvested energy is maximum, within a given time quantum ($T_{quantum}$), as shown in Fig 1. Therefore it can be inferred that

$$E_{curr} = .48E_{max}. \tag{13}$$

□

Theorem 1. *All nanoDESs are energy-wise stable, if* $packlimit = \left\lfloor \frac{H_{max}}{P_{trans}} \right\rfloor$, *where packlimit is the maximum number of packets flow possible through an edge,* H_{max} *is the maximum harvested energy of the transmitter nanoDES and* P_{trans} *is the transmission energy between the transmitter and the receiver nanoDESs of an edge.*

Proof. All nanoDESs must be energy-wise stable when the energy harvested is greater than the transmission energy for transmitting packets. According to Proposition 1, when $E_{curr} = .48E_{max}$, the harvested energy will be maximum. At this point, the transmission energy must be less than or equal to the harvested energy. So, the nanoDES gets its saturation point when the harvesting rate equals the transmission rate.

The total *packlimit* for an edge may or may not be used. Let the number of packets used be denoted as P, we have

$$\begin{aligned} P &= \lambda \times packlimit \\ packlimit &= \frac{P}{\lambda} \end{aligned}$$

where λ is a constant and $0 \leq \lambda \leq 1$. Further, $packlimit$ can be written as follows:

$$\begin{aligned} \frac{H_{max}}{P_{trans}} &= \frac{P}{\lambda} \\ P \times P_{trans} &= \lambda H_{max} \\ T &= \lambda H_{max} \end{aligned} \tag{14}$$

where T is the total transmission energy through an edge. From Equation (10), it is clear that for $packlimit = \left\lfloor \frac{H_{max}}{P_{trans}} \right\rfloor$, each nanoDES satisfies $T_r \leq h_{max}$, which is the sufficient condition for energy-wise stability of topology. Hence, the topology is energy-wise stable. □

Corollary 1.1. *The maximum packet limit of an edge (packlimit) is a function of the maximum energy level (*E_{max}*) of the transmitter nanoDES and the transmission energy required for a packet to pass through that edge.*

Proof. Let the maximum harvested energy within a given time quantum ($T_{quantum}$) be denoted as H_{max}. The harvested energy within a given time quantum $T_{quantum}$ is

$$\begin{aligned} H &= \left(\frac{E}{T_{max}}\right) \times T_{quantum} \\ &= \left(\frac{E_{max}-E_{curr}}{T_{max}}\right) \times T_{quantum} \end{aligned} \tag{15}$$

Substituting the value of E_{curr} from Equation 13, we get,

$$\begin{aligned} H_{max} &= \left(\frac{E_{max}-.48E_{max}}{T_{max}}\right) \times T_{quantum} \\ &= \left(\frac{.52E_{max}}{T_{max}}\right) \times T_{quantum} \end{aligned} \tag{16}$$

Let the transmission energy of a packet flowing through an edge of length d be P_{trans}. The transmission energy can be calculated using the equation given in [14]. From Theorem 1, the packet limit of an edge is

$$\begin{aligned} packlimit &= \left\lfloor \frac{H_{max}}{P_{trans}} \right\rfloor \\ &= \left\lfloor \frac{\left(\frac{.52E_{max}}{T_{max}}\right) \times T_{quantum}}{P_{trans}} \right\rfloor \end{aligned} \tag{17}$$

□

VII. Performance evaluation

A. Simulation setup

We evaluate the performance of the distributed topology algorithm using JAVA-based simulation. However, all required data for the simulation are collected from existing empirical data sources. The simulation environment having three-dimensional space contains the NM, which is considered to be located on the rib cage at a certain intercostal space [15], and the nanoDESs, which are assumed to be randomly inseretd at certain critical positions of clinically relevant coronary segments [16] involving LAD, RCA, and LCX. Since the stretching and shortening of heart muscles are considered to follow the models given in [17], the same models are considered for quantifying the periodic motions of the nanoDESs. The distance between the NM and a nanoDES varies due to the motions of the rib cage and the heart. So, data packets are delivered at the time when the distance between the rib cage and the heart is the minimal, and accordingly the transmission energy for sending packets is calculated. Furthermore, based on transmission energy the packet limit is decided. We executed each simulation for twenty-four hours of simulation time. We evaluate the performance of the proposed distributed topology control algorithm using the parameters given in Table I, considering three deployment scenarios as given in Table II.

TABLE I: Simulation Parameters

Parameter	Value
Energy per pulse	1 femtoJoule
Packet size	1000 Byte
Heart rate	68 per min
Rib-cage rate	18 per min
Energy of nano-battery	800 pJ
Minimum detectable strength	10 dB
Pulse width	100 femtosecond
MAC	TDMA

B. Packet delivery ratio

In the case of star topology, the nanoDESs which are situated at a relatively greater distances from the NM, such as LAD1, LAD2, and RCA7 consume significant energy, and after a certain time interval of continuous packet delivery, they do not have sufficient energy to send further packets. So, newly generated packets get dropped, thereby decreasing packet delivery ratio. In the distributed cases all the packets are sent through multiple nanoDESs, due to which the packets which are generated are successfully delivered. Consequently, packet delivery rate is almost 100%. At this juncture, it is noted that packets are assumed to be delivered at the time when the distance between a nanoDES and the NM is minimal, which is described in [9]. Furthermore, we assume that there is no timing error in communication. As shown in Fig. 3, some nanoDESs have less packet delivery ratio in the star topology compared to distributed topology.

C. Shutdown state

In Figs. 4(a) and 5(a), it is observed that the energy levels of some nanoDESs in the initial topology decrease rapidly, and after some time interval, the levels are reduced further to such extent that packets cannot be sent to the NM. However, in Figs. 4(b) and 5(b), it is observed that initially when the topology is star, the energy levels of the nanoDESs decrease, and after changing into new topology, the nanoDESs whose maximum harvesting energy are less than their transmission energy send their packet through the other PRNs, due to which each nanoDES proceeds to energy-wise stable state. As the harvested energy of a nanoDES in a given time quantum depends on the current energy level, all nanoDESs reach their saturation points, where the harvesting energy is nearly the same as the total transmission energy. It is noted that similar improvement in shutdown states in distributed topology is also observed in the case of deployment number 2.

D. Stability Factor

The stability factor of the system, denoted as SF, refers to the fraction of nanoDESs capable of participating in data dissemination every fixed time interval, which is described as $SF = \dfrac{\sum n_i}{I \times N}$, where n_i is the number of nanoDESs, which are in active states in i^{th} time interval or iteration, I and N are the total number of iterations and nanoDESs, respectively considered in the simulation. As shown in Fig. 6, the stability factor of the system when adopting distributed topology remains high and constant as compared with the star topology. It is noted that similar efficiency in stability factor in distributed topology is observed in deployment number 2.

E. Delay

In the star topology, the delay for transmitting data packets mainly consists of the queuing delay, which incurs when a nanoDES waits for its energy harvesting module to recharge its battery up to a threshold value from a shutdown state. While in the distributed topology, data packets are sent from the nanoDESs to the NM through multiple nanoDESs, so the delay consists of the waiting times of the data packets at intermediate PRNs until their turns to get routed. At this juncture, it is noted that propagation delay, which is of the order of nanosecond, is considered negligible. As shown in Fig. 7, most of the times or iterations the delay of the system in the distributed topology is less compared with the delay in the star topology. It is noted that similar improvements in the delay in distributed topology are observed in the cases of deployment numbers 1 and 2.

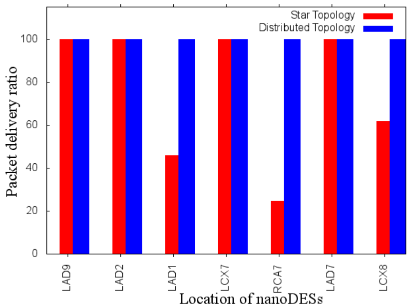
VIII. Conclusion

In this paper, we designed a distributed network topology for WNSNs used for CHD monitoring and studied the problems of efficient data delivery and shutdown of nanoDESs under different topological conditions. The study revealed that due to the shutdown events, nanoDESs are unable to send packets to the NM, leading to the loss of packets and decrease in the data delivery ratio. Until a nanoDES has sufficient energy to send packets to the NM, the packets wait in a queue, thereby increasing the queueing delay. In the proposed topology control protocol, the data packets are delivered through multiple hops according to their energy for harvesting and transmission. The simulation results established the superior performance of the protocol with respect to data delivery ratio, shutdown state, stability factors, and delay.

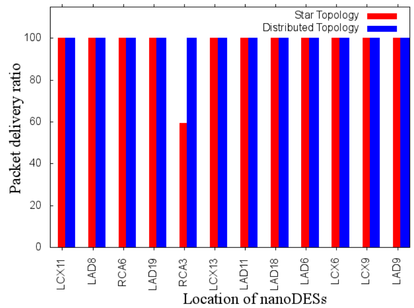
In future, we plan to run the proposed algorithm by taking into the account of the segmental deformations of the heart's chamber, which might impact on the amount of energy har-

TABLE II: The locations of nanoDESs and deployment scenarios

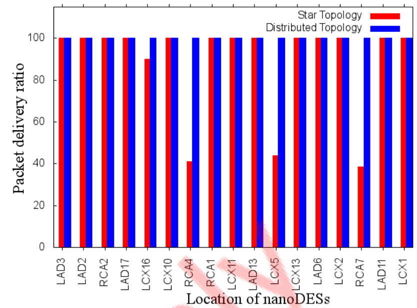
Deploy-ment	# of nano-DESs	Location of nanoDES																
1	7	LAD9	LAD2	LAD1	LCX7	RCA7	LAD7	LCX8										
2	12	LCX11	LAD8	RCA6	LAD19	RCA3	LCX13	LAD11	LAD18	LAD6	LCX6	LCX9	LAD9					
3	17	LAD3	LAD2	RCA2	LAD17	LCX16	LCX10	RCA4	RCA1	LCX11	LAD13	LCX5	LCX13	LAD6	LCX2	RCA7	LAD11	LCX1



(a) Deployment # 1 with low data rate

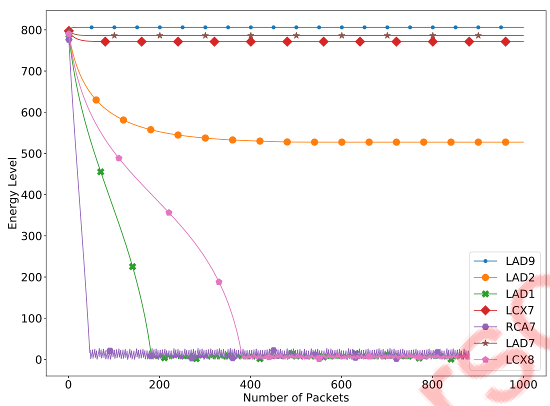


(b) Deployment # 2 with low data rate

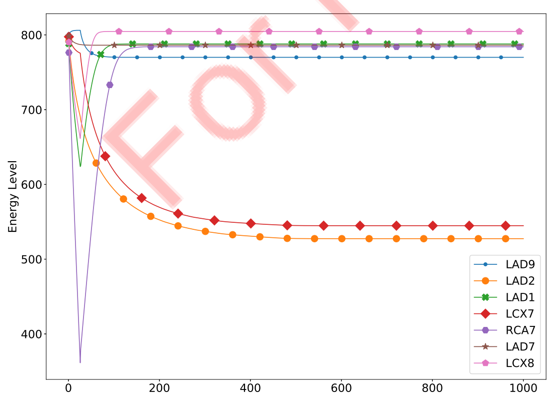


(c) Deployment # 3 with high data rate

Fig. 3: Packet delivery ratio in different deployment scenarios

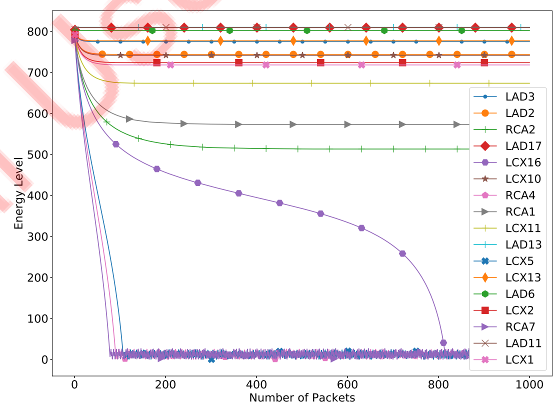


(a) Star topology

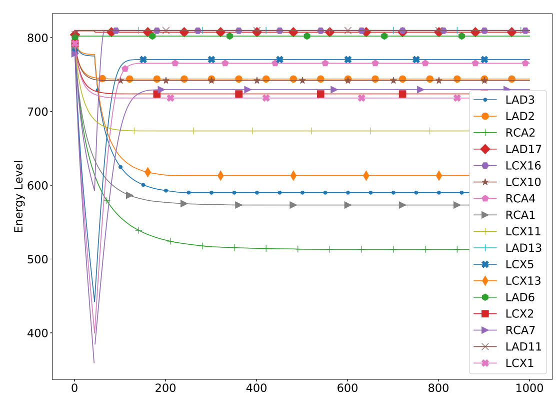


(b) Distributed topology

Fig. 4: Energy level in deployment # 1

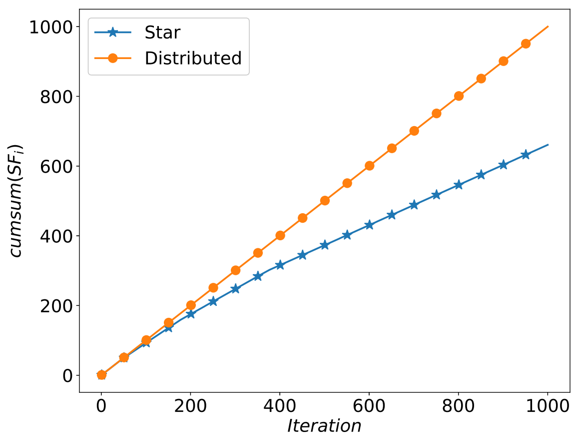


(a) Star topology

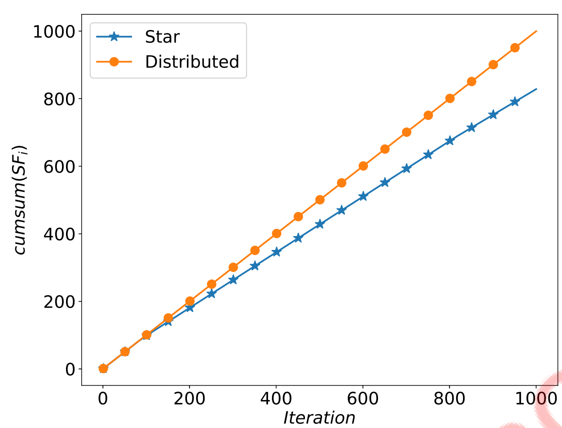


(b) Distributed topology

Fig. 5: Energy level in deployment # 3



(a) Deployment # 1



(b) Deployment # 33

Fig. 6: Stability factor of the system

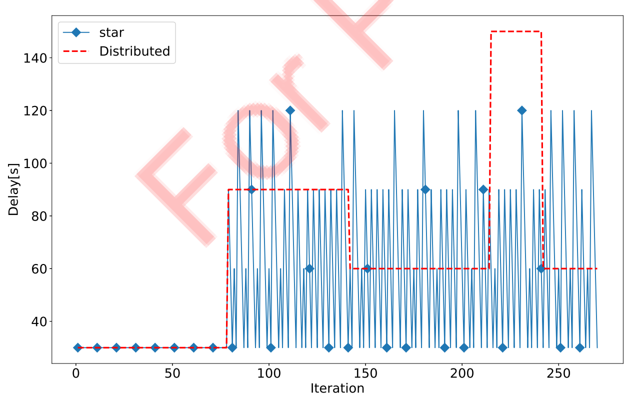


Fig. 7: Delay of the system in deployment # 3

vested by the nanoDESs. We will also explore the effect of different MAC protocols such as *polling*.

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