Pervasive and Mobile Computing 43 (2018) 49–63

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Survivable Path Routing in WSN for IoT applications

Manu Elappila *, Suchismita Chinara, Dayal Ramakrushna Parhi

National Institute of Technology, Rourkela, 769008, India

ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form 17 November 2017
Accepted 30 November 2017
Available online 6 December 2017

Keywords:
WSN
Network survivability
Congestion aware routing
Path survivability factor
SINR
IoT

ABSTRACT

Wireless Sensor Networks (WSN), enhanced communication protocols, distributed intelligence for smart objects, wireless radio frequency systems and several other technologies and communication solutions together enable the promising next generation Internet, called Internet-of-Things. This paper presents a congestion and interference aware energy efficient routing technique for WSN namely, Survivable Path Routing. This protocol is supposed to work in the networks with high traffic because multiple sources try to send their packets to a destination at the same time, which is a typical scenario in IoT applications for remote healthcare monitoring. For selecting the next hop node, the algorithm uses a criterion which is a function of three factors: signal to interference and noise ratio of the link, the survivability factor the path from the next hop node to the destination, and the congestion level at the next hop node. Simulation results suggest that the proposed protocol works better concerning the network throughput, end-to-end delay, packet delivery ratio and the remaining energy level of the nodes. The rate of packet drops is also observed to be lesser in the congested topology scenarios.

1. Introduction

The field of microelectronics has been advanced in the recent decades and led to the development of research on wireless networks of low cost, low rate, and low power network devices such as tiny nodes and sensors, etc. Wireless Personal Area Network (WPAN) [1] has a broad range of applications like wireless sensor networks (WSN), underwater acoustic networks, body area networks, industrial wireless networks, radio frequency identification (RFID) systems, machine-to-machine (M2M) communication systems and much more. These sensing, actuating, identification and other various processing devices are combined to form a network that achieves some shared objectives. They interact with the physical world pervasively with the aid of enhanced communication protocols and distributed intelligence, which constitute a novel paradigm called *Internet of Things (IoT)* [2,3]. "Anytime, anywhere, any media" was the vision for a long time in the past decades that pushed the communication technology into many advancements. Wireless technologies hold a pivotal role in this context. Today the ratio between the humans and radios achieving a value near 1 to 1. But shortly this proportion will increase by orders of magnitude which enables to integrate the radio devices in almost all objects. Then the word "anything" also added to the above vision which is nothing but the concept of IoT. However, these low-power low-rate radio devices are expected to operate autonomously for an extended period with small batteries of limited energy source. Since the unattended nature, replacement of those tiny batteries is impractical; hence the lifetimes of these multi-hop relaying networks directly depend on the residual energy level of its nodes. The actualization of the concept of IoT is possible through the integration of several different network infrastructures. RFID systems are used for the identification of the real-world object into digital format, and sensor networks are used for tracking the status of these objects. Performing any mechanical

* Corresponding author.
E-mail addresses: 514CS1009@nitrkl.ac.in (M. Elappila), suchismita@nitrkl.ac.in (S. Chinara), drkparhi@nitrkl.ac.in (D.R. Parhi).

https://doi.org/10.1016/j.pmcj.2017.11.004
1574-1192/

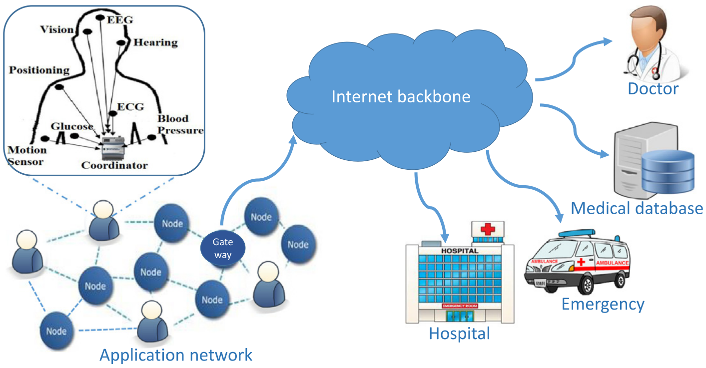


Fig. 1. IoT application scenario for remote healthcare monitoring system.

operations in the physical world is achieved through sensor–actuator networks. And M2M communications are used for automated data transmission and measurement between mechanical or electronic devices. All these different constituents together compose the backbone network infrastructure for IoT. At the same time, these application networks like sensor network have many similarities with other types of distributed systems; it has a lot of unique challenges and constraints such as self-management, energy limitation, congested packet transmissions, ad hoc deployment, unattended operation, high interference from peer relays, security restrictions, etc. This unique infrastructure nature of WSN demands a protocol designed that should fit for its specialties. If any node dies because of energy depletion, it may effectuate some remarkable changes in the topology that are significant enough to degrade the whole network. It may necessitate the reorganization of entire system. In IoT applications, it is a quite usual topology scenario that many senders are communicating to a destination node at the same time. Sensor nodes placed at different geographical area sending their collected information to the base station, communication between the RFID tags and the reader, data transmission between the actuators and the controller, communication between the nodes in the application network and gateway node to the backbone, etc. are some of the examples.

In the real-time networks with Multiple-Source Single-Sink (MSSS) topology, the relay nodes may suffer from high interference with the neighbors due to the greater degree of communication. Also, the receivers and relay nodes may get congested because of the excessive simultaneous packet transmissions. Fig. 1 shows an application of WSN in IoT based real-time scenario for the remote health care monitoring system. The proposed protocol is intended to work in such type of network topology. In this framework, the application subnet is formed with the wearable sensor nodes that continuously monitor the patient's heartbeat, blood pressure, and other critical parameters. Physician and hospital staff can access this information that may get stored in the database, which can also be used to trigger the ambulance service. Hospitals can use this scenario for continuously tracking the medical condition of critical patients and can be used in nursing homes to monitor the inmates. Using this type of health care applications physicians can remotely treat the patients and give advises to the caretakers. The gateway node that connects the application subnet to the outside Internet will act as the sink for the sensor network communications. This gateway (sink) node is capable of receiving and processing the data coming from different patients. A data forwarding technique is being proposed for this type of WSN application with the real-time data transfer. The critical nature of the application compels to have a reliable and stable route towards the sink for every source node in the system. Stability and the survivability of the paths are important in these types of applications. With the specialties of WSN, the lifetime of a network is the reflection of the lifespan of its nodes [4]. If a node in the network dies, it may lead to a situation that the topology suffers from some loss of connectivity. So routing protocols have to be designed such that it saves the battery power as much as possible, selects less congested relay nodes, chooses a path from source to destination with minimum interference [5]. Hence, energy efficient congestion and interference aware lifetime prediction routing protocols are paramount which motivated us to design an energy efficient survivable path routing protocol (SPR) in WSN. The proposed protocol is a data forwarding technique which maintains the network survivability by choosing the path which has the higher survivability factor (explained in Section 3.3). It also tries to minimize the congestion at the nodes by including the network traffic information (congestion level of a node) from the physical layer as the route choosing factor. The routing choice decision-making process also includes the signal strength information of the previously received packets. For efficient and reliable communication in IoT networks, designs at different layers of the protocol stack have to be developed accordingly. So we aim to frame a cross-layer design that spans different layers, i.e., stable routing in the network layer, effective access control and transmission power control in MAC sub layer, reliable and light-weight transmission control at the transport layer, and a middle-ware technique to integrate the WPAN application subnet with the Internet backbone. As the first step, this paper proposes a data forwarding method at the network layer, and the protocols at other layers would also be developed in future work to assist this protocol and to have a complete cross-layer design for an efficient communication model.

The paper is organized as follows: section two presents a brief survey of related routing protocols designed for WSN applications. In section three, the proposed protocol is presented. In section four, the evaluation of the newly proposed scheme and the simulation results are presented. Finally, section five concludes the paper.

2. Related works

A smart gateway architecture of remote healthcare is proposed in [6]. Y. M. Huang et al. in [7] present a group based data collection and transmission technique to surveil elderly patients. They discuss the security issues in data transmission and also propose a monitoring application prototype. A 6LoWPAN based gateway architecture is proposed in [8] for real-time health care networks. Learning automata based congestion avoidance scheme in data link layer for many-to-one traffic pattern in health care WSNs is presented in [9]. But collecting the congestion information from the physical layer and using it for the path selection process would have more impact on the network topology to keep it more survivable. In real-time healthcare systems, it is crucial that the routes from the patient's sensing device to the controller base station are interference and congestion free and the network should always be connected. Gradient-based routing techniques are more suitable for these flat topologies.

Routing protocols in WSN -. Flooding is the simplest routing technique in which a sender node broadcasts the data packets to all of its one-hop neighbors [10], which in turn rebroadcast the packet to their neighbors and so on until it reaches the destination. Sensor Protocols for Information via Negotiation (SPIN) [11] is a family of negotiation-based, data-centric, and time-driven flooding protocols that work upon the negotiation and handshaking with the neighbor nodes before transmitting data, which allows the nodes to avoid unnecessary communications. Directed diffusion [12] is a query-driven protocol in which the sink node broadcasts an interest packet to its neighboring nodes, and they again send it to their neighbors, and this continues throughout the network until it reaches the source. Each node establishes a gradient towards the sink at the time of interest forwarding. The source sends back the data to the destination through this gradient. The authors of [13] proposes an energy-efficient cluster based routing for micro sensor networks. A survey of different clustering approaches for ad hoc networks is presented in [14].

Routing with energy efficient lifetime maximization -. There exist some routing techniques in sensor networks that utilize the limited available resources of its nodes more efficiently. They aim to find the minimum energy path for optimizing the usage of battery power of a node. Energy Aware Routing Protocol proposed by Shah et al. has an underlying idea that is for increasing the network survivability [15]. Continually utilizing the optimal paths may not be effective for long-term connectivity from the perspective of the network lifetime. It has been necessitated to use also the sub-optimal routes sometimes. This modification ensures that the optimum path is not suffering from energy depletion, and hence the network will be gracefully degrading as a whole rather than get partitioned. Their routing protocol would discover multiple paths between the source and the destination. Probability is assigned to each path using some energy metric, and the nodes randomly choose one among them depending on these probabilities when there is a packet to send. Dayang et al. make better routing choice in [16] by considering the residual capacities of the batteries of the network nodes and the total consumed energy along the path from source to destination. It is a better approach since it selects a route for the communication only for a predetermined cycle time. So during each cycle, the nodes that are not in the chosen path can get scheduled to sleep. Cost-effective Maximum Lifetime Routing Protocol [17] selects a route based on a parameter which is a function of the total routing cost and the minimum residual energy among all nodes along that path. The authors of [18] proposes a logical tree structure routing which uses directed acyclic graphs and the concept of the rank of nodes to detect the loop problem and to solve it. In [19], an adaptive cross-layer design that can be integrated with the IEEE 802.15.4/Zigbee networks is presented. It tries to configure the mac layer based on traffic conditions and network topology. They developed an adaptation module that spans entire protocol stack and collects routing information from the network layer and application specific information. The principle of opportunistic routing theory and multi-hop relay decision based protocol for optimizing the energy efficiency and hence maximizing the network lifetime is proposed by Luo et al. in [20]. The routing decision is made based on the geographic distance to sink and the residual energy.

Congestion and interference aware routing -. The authors in [21] propose an interference-aware routing that works in two rounds. In the earlier one, it discovers the shortest path between the sink node and source node. It blocks the neighbors of the nodes along that shortest path from getting selected in the second round. So, the final resultant routes discovered after the second round are away from each other for a distance twice of the transmission range; that helps to minimize the interference. Network Coding Based Probabilistic Routing scheme that improves the bandwidth efficiency, reliability, energy efficiency of the network and also alleviates the broadcast storm problem in clustered sensor networks is present in [22]. Abdulrauf et al. propose a congestion detection technique for multipath routing and balancing the load among the network nodes in [23]. Route selection has been made based on the distance between source and destination, buffer occupancy of nodes and relative success rate (RSR) value of nodes. RSR value that helps for the congestion control is the ratio between the number of packets transmitted at the MAC layer to the number of packets forwarded at the network layer. In [24] least path interference beaconing protocol (LIBP) is proposed. It is a frugal routing protocol for IoT. Sensor nodes select the least path interfering parents as the relay node from the routing spanning tree rooted at the sink node that built with a periodic beaconing process. In [25] authors propose a genetic algorithm based multipath routing that tries to maximize the fitness function that is the cost function based on the distance between next hop and destination, the distance between the current node and next hop node, and hop count of the next hop. Multiple-criteria decision-making procedure based routing is proposed in [26]. Virtual potential fields are created based on the concept of distance between nodes as the potential energy. Data packets are forwarded to the next node based on the maximum joint driving force which is a function

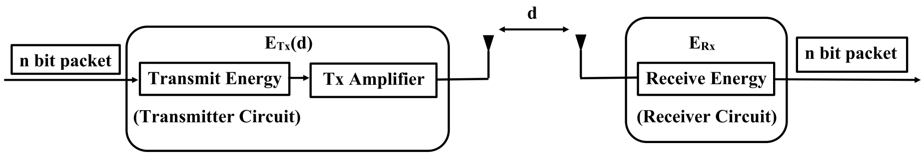


Fig. 2. First order radio model.

of virtual-potential field based on the distance from the node to the sink, that based on the distance between the node and its neighbors, and the residual energy level factor. Renjian et al. propose a reliable routing based on coalition game theory in [27]. Each participant node selects its strategy based on characteristic function that has three components: the rate of packets forwarding, the rate of correctly reporting event and the rate of remaining energy. Rate of packets forwarding is the ratio between the number of packets a node receives from neighbors and the number of packets forwarded by node. Rate of correctly reporting event is the ratio between the number of event correctly reported by a node and the total number of event reported by that node. Remaining energy rate is the ratio between remaining energy of a node and its initial energy. An adaptive path scheduling mechanism is proposed in [28] as part of a cross-layer design for video transmission over WSN. Routing choices are made based on a path score which is a weighted sum of four factors: minimum remaining energy along the path, minimum buffer capacity along the path, hop count measure for the path, and finally the path reliability measure. Path reliability measure is the ratio of the number of delayed packets at the destination to the total packets received.

3. Proposed protocol: energy efficient survivable path routing (SPR)

The proposed protocol is a data-centric gradient based routing technique like Directed Diffusion. The sink node initiates the route establishment with sending an interest packet which gets expedited throughout the network. This interest dissemination sets up gradients at each node that help to direct the data towards the destination. At the end of route discovery, multiple paths are established that can be used by the source nodes to forward the data packets. Each gradient is associated with some parameter such as survivability of the path, link quality (interference) and congestion in the next hop node. These metrics are used to estimate the quality of the routes and to select one among them. The protocol needs only local information at every node in the network, i.e., each intermediate node maintains the information about their one-hop neighbors. It is a dynamic routing technique. It uses the route setup mechanism in [16] which works with the dynamic game theory approach. The network characteristics and energy model of the system are as follows.

3.1. System model

We are assuming a 2D-network model consisting of sensor nodes with the following assumptions:

- All nodes are stationary.
- There is only one sink node to which the packets from multiple source nodes are destined.
- All nodes are homogeneous, i.e., they have similar communication and processing capabilities, and the same initial energy at the time of deployment.
- Nodes are location aware. For the simulation purpose, 2 - dimensional x and y coordinates are used to locate a node.
- The distance between the nodes is the Euclidean distance between them.
- All nodes are deployed randomly in the topological area.
- We consider MSSS topology, that is the network topology where more than one sensor node can gather, receive and transmit data to the sink simultaneously [29].

3.2. Energy model

The first order radio model is a commonly used energy consumption model [30–32]. Fig. 2 describes the radio model for the transmission and reception an n-bit message.

In battery powered WSNs, the preeminent energy dissipating module is the radio communication. The presumption of homogeneous nodes allows the conjecture of same transmitting rate r for all nodes. So the energy consumed while transmitting an n-bit message to a receiver located d distance apart can be formulated as the equation,

$$E_{tx}(d) = n\, r\, \phi_{cir} + n\, r\, \phi_{amp}\, d^{\alpha} \tag{1}$$

where, ϕ_{cir} is the energy dissipation needed (distance irrelevant) to operate the transmitter circuit, and ϕ_{amp} is the distance-related factor that represents the transmitter amplifier. The exponent α denotes the path loss component, usually its value falls into the range [2 , 4], i.e., for multi-path fading $\alpha = 4$ and $\alpha = 2$ for free space.

Table 1
Notations.

Notation	Explanation
$G = (N, E)$	Network graph, N = set of nodes, E = set of edges
(i, j)	Link between node i and node j
d^e_{ij}	Euclidean distance between node i and j
(x_i, y_i)	X and Y coordinates of node i
κ_i	Congestion level at node i
τ_i	Traffic input rate of node i
ς_i	Output service rate of node i
ρ	Path survivability factor
a	The lowest of residual energies of the nodes along a path
c	Total Energy cost for transmission through a path
$\theta\,(e_i)$	SINR value of the link e
$p\,(T_e)$	Transmission power of the transmitter T_e
$G\,(T_e, R_e)$	Path gain between the transmitter T_e and Receiver R_e
$I_f\,(e_i)$	Interference at the receiver of the edge e

The energy consumption for receiving an n-bit message at the rate r mainly depends on the dissipation in the circuit. Therefore,

$$E_{rx} = n\, r\, \phi_{cir}. \tag{2}$$

Hence, for a particular intermediate node i, the energy consumption for communication E_i for relaying an n-bit message at the rate r over the distance d can be defined as,

$$\begin{aligned} E_i &= E_{tx} + E_{rx} \\ &= n\, r\, \left(2\, \phi_{cir} + \phi_{amp}\, d^{\alpha}\right). \end{aligned} \tag{3}$$

3.3. Notations and assumptions

The network consisting of sensor nodes communicating to each other can be represented as a graph $G = (N, E)$ where N is the set of all nodes and E is the set of links between the nodes. In the communication network, a link exists between two nodes if both are in the transmission range of each other. That is, if i and j are two nodes in the network, a link (i, j) in the graph (i.e., $(i, j) \in E$) denotes that i is in the transmission range of j and vice versa. The Euclidean distance between the node i and j is represented by d^e_{ij}, and the maximum transmission range of a node is represented by R, then the set of edges E can be written as, $E = \left\{(i, j) \;/\; d^e_{ij} \le R,\ i, j \in N\right\}$. N_i denotes the set of all neighbors of node i. i.e., $N_i = \{j \;/\; i \neq j \wedge (i, j) \in E\}$. S represents the sink node in the network. (x_i, y_i) denotes the x-coordinate and y-coordinate of the node i. Further, the congestion level of a node is represented by

$$\kappa_i = \tau_i / \varsigma_i \tag{4}$$

where τ_i is the input traffic rate and ς_i is the service rate. Input traffic rate is the number of packets flows into the physical layer of the protocol stack of a node in a unit time. Similarly, service rate is the number packets flows out downwards to the channel in a unit time. Since the capacity and fullness of the interface queue plays a crucial role in changing the traffic load of a node, congestion information has to be collected from the physical layer (see Table 1).

One of the existing algorithms in [16] is an energy aware lifetime prediction routing protocol which is efficient in utilizing the nodes energy, and hence increases the network lifespan. The basic idea is to improve the survivability of the network. The protocol should try to ensure the network connectivity as long as possible, and the energy level of the entire topology is in an almost same range. The route selection criteria include a metric called Path Survivability Factor. The survivability factor of a path is the ratio of the minimum value of available residual energy among every node along that path to the total consumed energy for communication through that path. That is, if c is the total energy consumption of the path L and a is the minimum power available value among the nodes in path L, then a/c can be defined as the Path Survivability Factor.

$$\textit{Path Survivability Factor}, \quad \rho = f(a, c) = \frac{a}{c}. \tag{5}$$

We consider multiple source topology where there is more than one source node transmitting to the base station at the same time, which may cause more interference in the medium. So typical routing strategies would not work well in this topology. Channel aware and interference sensitive techniques should also incorporate for having more efficient algorithms. The route selection criteria should include the information about the link between the current node and the next hop node. The best such information is the SINR value of that node.

Furthermore, the interference on the medium influences the energy consumption also. That is if there is high interference on a link then the communication through that link demands more transmission power at the transmitter. In a multi-hop WSN with multiple sources, the power consumption may also get decided by the SINR value of the channel; hence, stronger the signal interference more the power consumption. Suppose communication is taken place on a link that has low interference, then the transmitter will send the signal with a particular transmission power; if the interference along that link increases, it should have to increase the transmission power for maintaining the signal strength same. That is for keeping the communication quality same; more transmission power has to use when the signal interference is stronger.

Theoretically, the SINR is defined as the ratio of the strength of the transmitted signal to the sum of interference and the ambient noise [33]. In the case of a transmission edge e_i, the amount of interference and noise at the receiver R_{e_i} can be expressed as,

$$I_f\left(e_i\right) = \sum_{m:m\neq i} G\left(T_{e_m}, R_{e_i}\right) p\left(T_{e_m}\right) + \eta_i. \tag{6}$$

Here $G\left(T_{e_m}, R_{e_i}\right)$ is the path gain between the transmitter T_{e_m} on the link e_m and the receiver R_{e_i} on the edge e_i. $p(T_{e_m})$ is transmission power of the transmitters T_{e_m} on edge e_m. And finally η_i is ambient noise around the receiver node R_{e_i}.

Then the SINR value of an edge e_i can be defined as,

$$\theta\left(e_i\right) = \frac{G\left(T_{e_i}, R_{e_i}\right) p\left(T_{e_i}\right)}{I_f\left(e_i\right)}. \tag{7}$$

From the above equation, it can be seen that when $I_f\left(e_i\right)$ increases, for maintaining the same SINR value on the link, the transmission power $p(T_{e_i})$ has to rise accordingly. But, if $p(T_{e_i})$ increased, the other links in the topology may experience more interference. Therefore, those links also need to increase their transmission power to maintain the same signal strength and hence the communication quality. It may amplify the energy consumption of the nodes and may lead to less network lifetime.

3.4. The routing strategy

The algorithm is designed to work with the principle of optimality. At each intermediate node, it will try to find out the best relay node for the next hop from all the available possibilities, so that the downstream path (rest of the route towards the destination) is optimum. For the selection of next hop node, the algorithm uses a Path Choosing Factor (PCF) which is a function of three components, survivability factor of the path to the destination through the next hop, signal to interference ratio of the next hop node and congestion level of the node at the next hop. So, it finds the node which is having high path survivability factor, less congestion level, and high signal to interference ratio. Hence gradually it finds the best possible route at that instant of the network conditions. Survivability factor is a fraction that has the lowest of the residual energies of the nodes along the path in the numerator and the total energy cost for the transmission up to the destination in the denominator. Hence it assesses how likely the route gets disconnected if chosen and what is the total energy requirement. Congestion information will help to choose the less congested node as the next hop, and SINR component tries to reduce the interference from other nodes at the next hop. By formulating the PCF as the function of these three factors, it makes a trade-off between the network survivability, interference from peer transmissions, and congestion at the network nodes.

It considers MSSS topology for IoT applications in which multiple source nodes send their sensed data to the base station simultaneously and hence may have interference in the communication medium. The protocol is designed to route the data packets through the path having minimum interference and the congestion at the relay nodes. This proposal is a destination initiated query-driven reactive routing protocol. Here, the sink node starts the route discovery process by sending an interest message. The protocol works in three phases.

- **Route Discovery/Setup phase:** Destination node initiates by broadcasting the interest packet (Route Discovery Packet) to all it neighbors that in turn rebroadcast it to all their neighbors and so on. At the end of this phase, multiple paths between source and destination are found out, i.e., it will find all the topologically possible paths from the source to the destination. This phase creates the routing table.
- **Data Communication/Forwarding phase:** During this phase, the source node sends the data to the next hop node that is selected from its routing table based on the defined Path Choosing Factor, by Eq. (8). Every intermediate node also selects their relay nodes from their respective routing tables based on this PCF. The routing table has been created at every node at the end of the setup phase that contains the data about only their neighbors.
- **Route Management/Maintenance phase:** This phase works to maintain the routes fresh and valid. And also, this phase plays a crucial role to make the protocol work better. Each node would forward the data packets by checking whether its route purge credentials (i.e., remaining energy and components of PCF) are below a threshold. If so, it informs the sink node for starting the route purging. In our simulations, we set the threshold to ninety percentage of its value in the previous round. Each route purge makes a new round, starting from the route setup. When sink node receives a route purge packet, it will send the maintenance packet to its neighbors. And the process works in the same way as the Setup Phase. Each node in the network updates their routing table entries, upon the reception of these packets. This phase will help to keep the information on the congestion, interference level, and the residual energy of the neighboring nodes up to date by modifying the route table entries.

At every node, the next hop node is selected from its routing table, based on the PCF. PCF is a function comprises three factors; the survivability factor ρ of the path to the destination through that next-hop, SINR value $\theta(e)$ of the link e between the current node and the next hop node, and the congestion level κ at the next-hop. That is,

$$PCF = (\alpha * \theta(e)) + (\beta * \rho) + (\gamma * (1 - \kappa)). \tag{8}$$

The SINR value is the Signal to Interference and Noise Ratio of the link. In Route Discovery phase when a node receives interest packet, it calculates the signal strength of the received packet and then the signal-interference ratio of the link. And it is stored in the routing table. Periodically it is updated using the route maintenance phase.

The congestion level at a node is calculated using the Eq. (4) in the previous section. Each node includes the information about its congestion level in the route discovery packets before forwarding it in the setup phase. Upon reception of these packets, each node inserts this information into their routing table. And in the route maintenance phase, these entries get updated as the maintenance packet carry the new information.

α, β, and γ values are used for setting different weights on the three components, $\theta(e)$, ρ, and $(1 - \kappa)$ of the PCF. Their values can be chosen according to the need for imposing the dominance for these three components in the path selection. In our simulation, all three weighting coefficients are equally considered as, $\alpha = \beta = \gamma = 1/3$, to indicate equal influence by all the components in PCF. The values are normalized such that,

$$\alpha + \beta + \gamma = 1. \tag{9}$$

If $\alpha = 0$ and $\gamma = 0$, then the proposed routing will be biased for only the network survivability. Similarly, if $\alpha = 0$ and $\beta = 0$, then it will work to reduce the network congestion by selecting the less congested node as the next hop. And if $\beta = 0$ and $\gamma = 0$, then the protocol will choose the node which has higher Signal to interference ratio as the next hop.

If most of the network nodes are having the energy level below a minimum value, then β can have a higher value so that the component ρ will dominate in PCF. If the network has high interference from peer nodes, then α can have a higher value so that $\theta(e)$ can have higher dominance. If the application traffic is too high and the nodes congested with packets, then γ can have higher value, so that $(1 - \kappa)$ will have greater influence in the PCF.

3.5. Algorithms and flowcharts that explain the working of the protocol.

Variables:
a_value ← residual energy of the node that has the minimum energy among all the nodes in the path towards the sink.
c_value ← total energy required for a packet to reach the sink node.
*SINR_* ← SINR information of the current node.
*kappa_* ← Congestion information of the current node.

Algorithm 1 Algorithm for the Route Setup phase

1: Sink node creates the Route Discovery (Interest) packet.
2: Store the value in the fields of the Route Discovery Packet as,
    a_value = residual energy of the sink.
    c_value = 0.
    SINR_= 0.
    kappa_= 0.
3: Sink node broadcasts the Route Discovery Packet to its 1-hop neighbors
4: Each intermediate node executes Algorithm 2, upon the reception these packets.
5: If the current node is a source node, do not broadcast the packet further.

4. Simulation results and discussion

Simulations are carried out in Network Simulator-2 (NS-2.35). In each simulation the proposed protocol is compared with the Directed Diffusion Routing Protocol [12], Sub-Game Energy Aware Routing Protocol (SGEAR) [16], Congestion Detection Technique for Multipath Routing and Load Balancing (CDTMRLB) [23].

The proposed protocol is a gradient based routing which uses the local information at each intermediate node, similar to directed diffusion. SGEAR is a technique that tries to maximize the network survivability. Continually utilizing the optimal path may not be efficient for long term connectivity from the perspective of network lifetime. It finds multiple paths towards the destination and uses sub optimal paths occasionally. Their idea is not to use only the best path to route the packets to the destination but use the suboptimal path also intermittently. Hence the nodes in a single route will not get energy depleted, and network not gets disconnected. SGEAR uses a route selection criterion which is a function of residual energy and total transmission energy cost of a path. But for better results, the interference information of the nodes is also to be considered for stable routing performance. If interference is more on the channel, then the nodes need to use higher transmission power, to ensure the signal quality at the receiver. So, in our approach, we include interference information also in the route choosing

Algorithm 2 Algorithm that executed by intermediate nodes

```
if RT doesn't contain an entry for that path then
    Create a new entry in the RT
    Store the values of the fields in the Interest packet i.e., a_value, c_value, SINR, kappa_ of the next hop node.
    Call Algorithm 3 to update the Interest packet.
    Forward to its 1-hop neighbors.
else if Seq. No of the packet >Seq. No in the Packet then
    Update the fields i.e., a_value, c_value, SINR and kappa_ using the information in the new packet.
    Call Algorithm 3 to update the Interest packet.
    Forward to its 1-hop neighbors.
else if Seq. No of the packet = Seq. No in the Packet AND
        hop count of the packet < hop count in RT AND
        PCF calculated from packet > PCF calculated from RT then
    Update the fields i.e., a_value, c_value, SINR and kappa_ using the information in the new packet.
end if
```

Algorithm 3 Procedure: Update Interest Packet

```
Source address field in the packet = index of the current node.
Increment hop count in the packet.
if residual energy of the current node < a_value in the packet then
    a_value = current node's residual energy.
else
    retain the existing a_value in the packet.
end if
Add communication cost from the previous node to the current node with the existing c_value.
Get the SINR information of the current node from the PHY layer and store it the packet.
Get Congestion information of the current node from the PHY layer and store it in the packet.
```

Algorithm 4 Algorithm for the Data forwarding phase

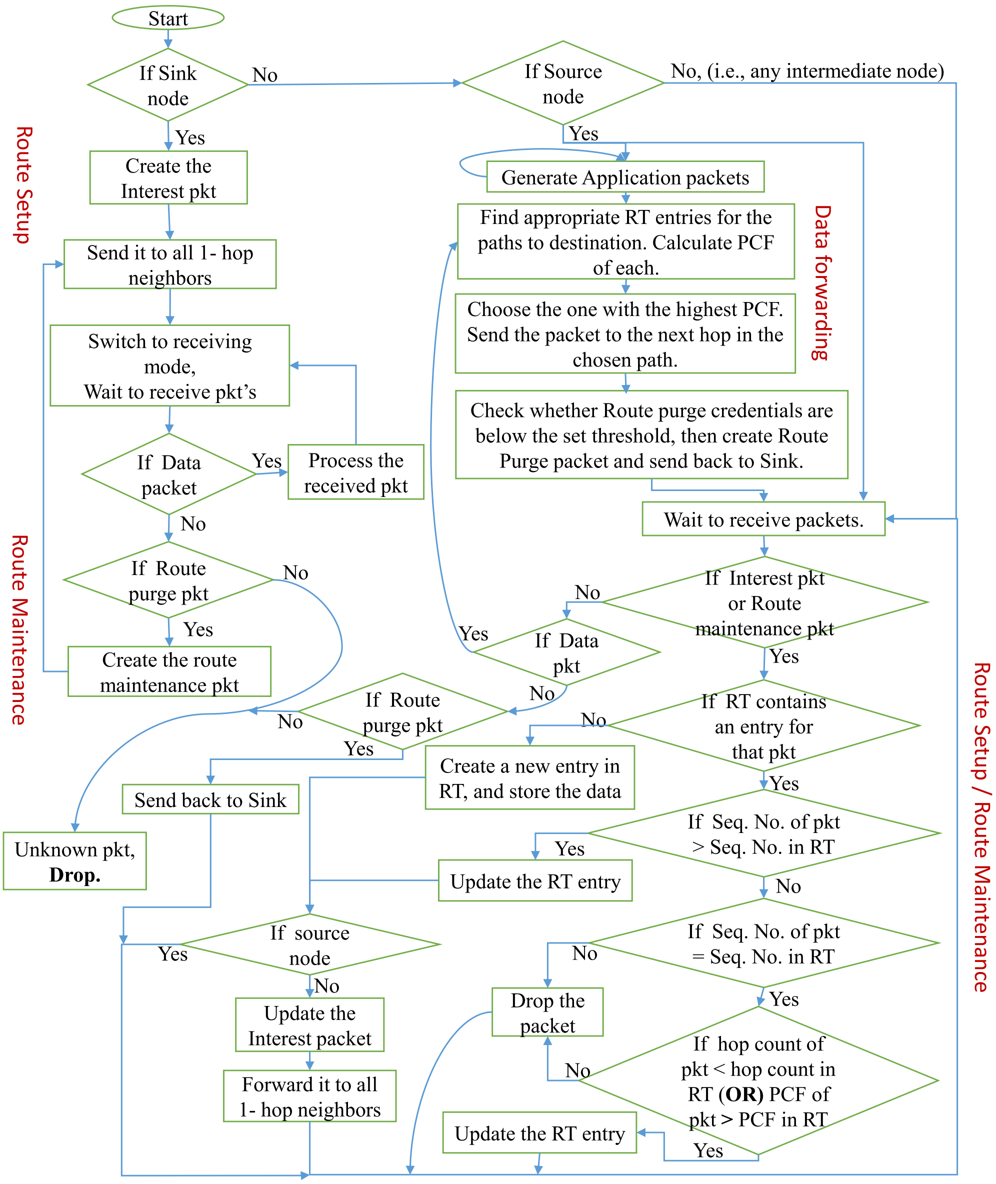
```
1: Once Interest packet reaches a source node, it initiates the data communication.
2: For sending the data, it will first select a path from the Routing Table RT.
3: It calculate Path Choosing factor (PCF) of next hop node in each path.
4: Among multiple paths, choose the one with the highest PCF.
5: Forward data to the next hop node.
6: Each intermediate node calculate the PCF of their next hop neighbors and forward to the one which has the highest value.
7: Repeat Step 6 until the data packet reaches the destination.
```

Table 2
Simulation parameters.

Parameter name	Parameter value
Propagation mode	Shadowing model
Transmitting range	40 m
MAC protocol	IEEE 802.15.4
Traffic flow	CBR
Data transfer rate	10 pkt/sec
Packet size	50 Bytes
Initial energy	100 J
Cycle time	10 s

factor. CDTMRLB is the congestion based technique, which uses relative success rate, buffer occupancy ratio, and distance from next hop node to the destination. It tries to find the route which is less congested and buffer occupied. In our proposal, we calculate the congestion level κ at the physical layer which is below the network interface queue in a nodes structure. And hence it will take the packets that come out from the queue for transmission, into the consideration for calculating the congestion level. And the path survivability factor ρ will include the effect of the number of hops to the destination in the total route cost factor. So the actual distance that needs to be traveled by the packet towards the destination is addressed. By considering all these, SGEAR, CDTMRLB, and Directed Diffusion are chosen for the comparison.

Network nodes are randomly deployed in an area of 100 m $\times$ 100 m 2-Dimensional space. Fig. 3 shows an example topology. Simulations are carried out by eventually increasing the number of source nodes in the network. The number of such source nodes that simultaneously communicates to the sink is increased up to the ten percent of the total number of nodes in the network. Other simulation parameters are given in the Table 2.



Nodes spanned across the topological area have to keep their energy level in same range to perpetuate the survivability of the network. Fig. 4 shows the remaining energy level of the nodes in the network topology. The source nodes in the network initiate their data packets at a rate of 10 packets per second, and they travel along multi-hop paths to the destination node. The figure compares the remaining energy level of the nodes after ten rounds of data exchange between the source and destination. From the figure, it is clear that for directed diffusion protocol, the network nodes have more disparity in their energy strength. But, for the proposed protocol the energy strength of the network nodes are almost in the same range. So it may help to keep the network connected for an extended period and make the network more survivable. The maintenance phase of the proposed protocol aids to achieve this, i.e., every data packets are forwarded by the relay nodes after checking whether it goes below a certain energy threshold. If remaining energy capacity of any node dropped below that threshold, it rearranges the routes and updates the path selection metrics. Hence, all nodes in the network maintain their battery capacity in the same range which prolongs the network connectivity.

Fig. 5 denotes the comparison of packet delivery rate of the proposed protocol with existing SGEAR and Direct Diffusion routing techniques. Different simulations are carried out with the different number of source nodes in the network those send data to the destination node simultaneously. From the figure, it can be concluded that the proposed protocol outperforms than the existing protocols. In all the cases the packet delivery rate for the new protocol is higher than the existing protocols.

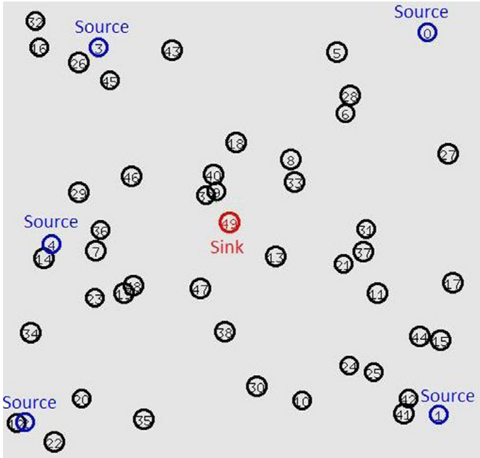
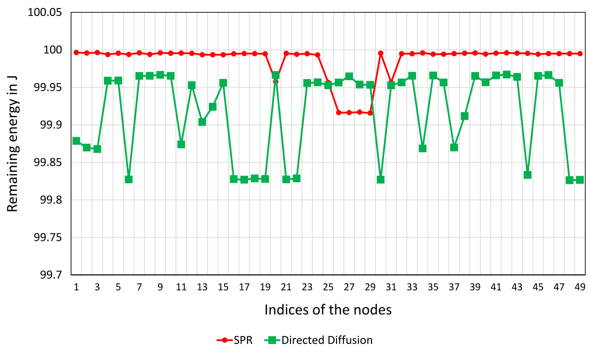
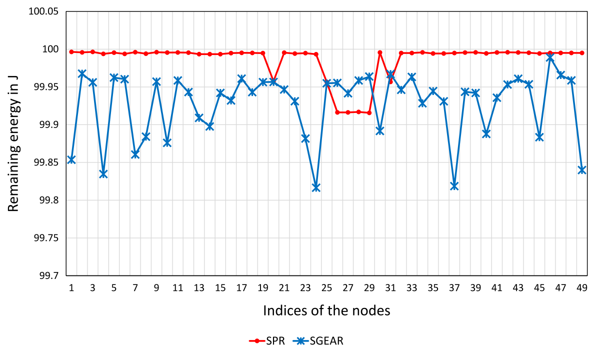


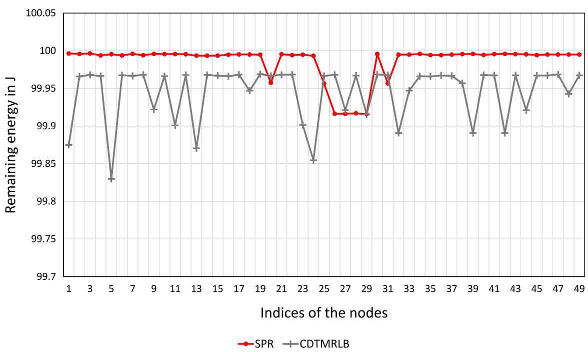
Fig. 3. Example topology.



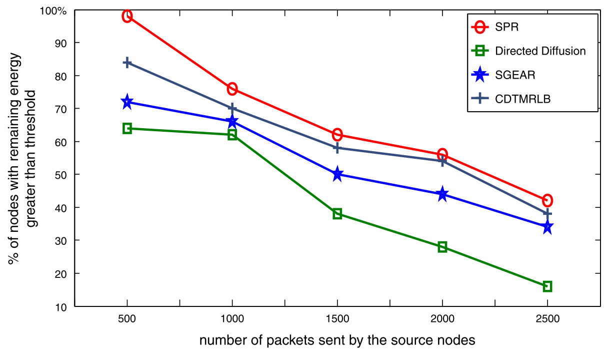
(a) SPR vs. directed diffusion.



(b) SPR vs. SGEAR.



(c) SPR vs. CDTMRLB.



(d) Nodes with remaining energy above the threshold.

Fig. 4. Remaining energy level of the network nodes in the topological area.

This is because, there are multiple source nodes in the network, which will create interference on the other nodes. Since the SGEAR protocol only considers the energy factor for the selection of the route, it may select the paths which are congested enough to drop the packet. And hence it is not able to reach the packet at the destination. So in the SGEAR protocol, the number of received packets at the destination is less. On the other hand, the proposed survivable path routing protocol will also consider the congestion in the communication medium for selecting the routing choice. It is more focused to select a path which has as less interference as possible. So the proposed algorithm can reach more packets at the destination. The number of packet drops is less in the new protocol.

Fig. 6 shows the average end-to-end delay for the data packets in the network. Delay will increase as there is more number of peer source nodes in the network, and hence the increasing graph shows the proposed protocol performs better, also in

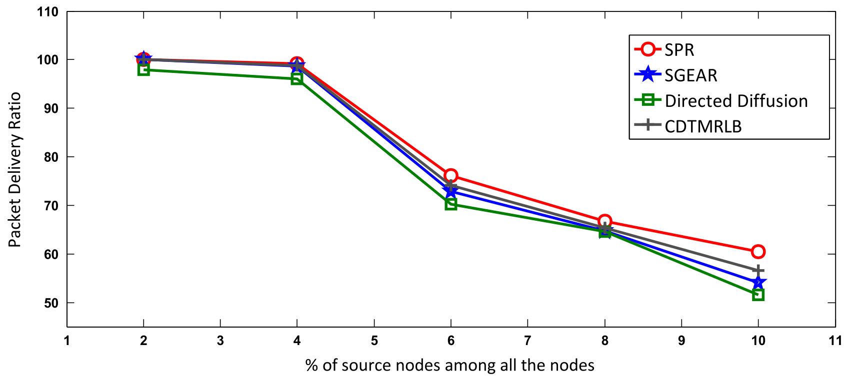


Fig. 5. Packet delivery ratio.

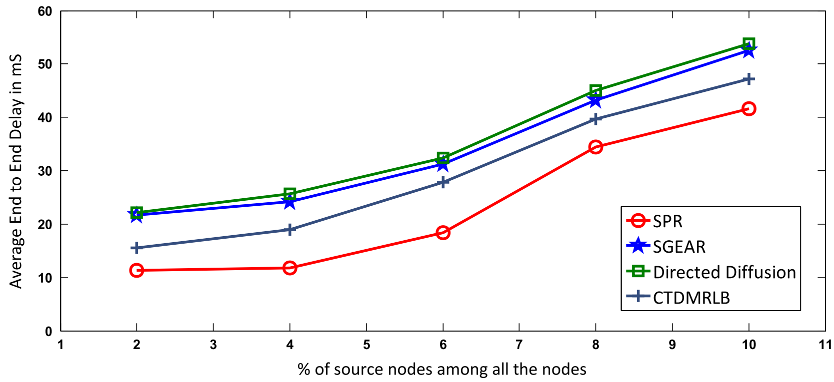


Fig. 6. Average end-to-end delay.

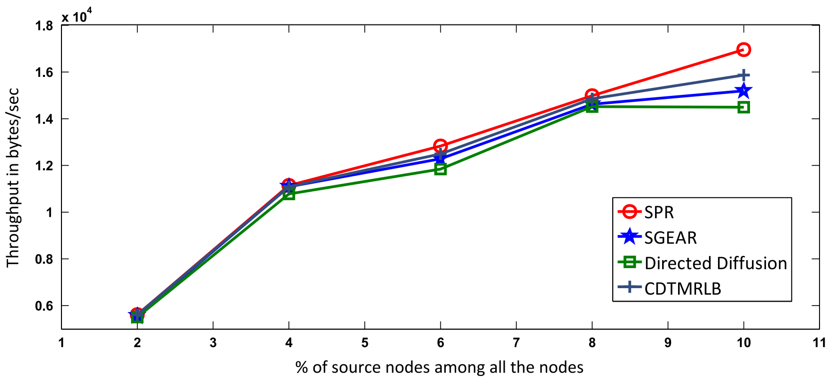


Fig. 7. Network throughput.

the case of end-to-end delay of the packets, as compared to the existing works. As the number of source nodes in the network increases the congestion also increases and that may incur more queueing delay for the data packets at the relay nodes. It selects the path that is less congested among the paths towards the destination, hence it works better to reach the packet at the destination early.

Fig. 7 shows the throughput comparison between the existing and proposed protocols. In our simulation, we measured the throughput in bytes per second. If a protocol can deliver more packets to the destination in the specified time, it may have higher throughput. And it will utilize the channel in more efficient manner. From the figure, it can be observed that the proposed protocol is having higher throughput when compared to the other protocols. Since the proposed protocol can assure higher delivery rates for the data packets in the network, it could have the higher throughput.

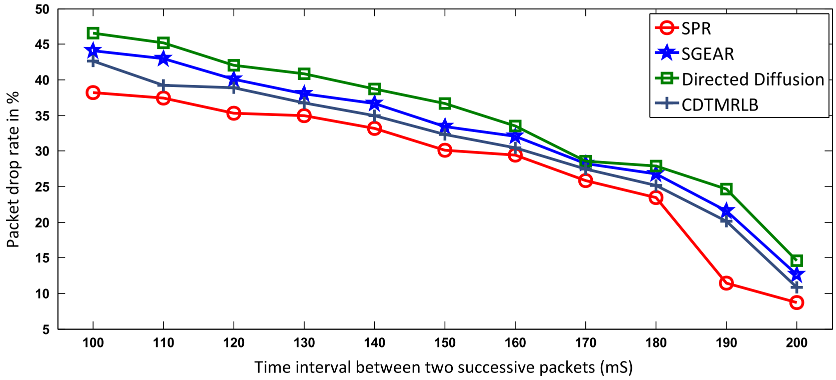


Fig. 8. Average packet drop rate at decreasing traffic load.

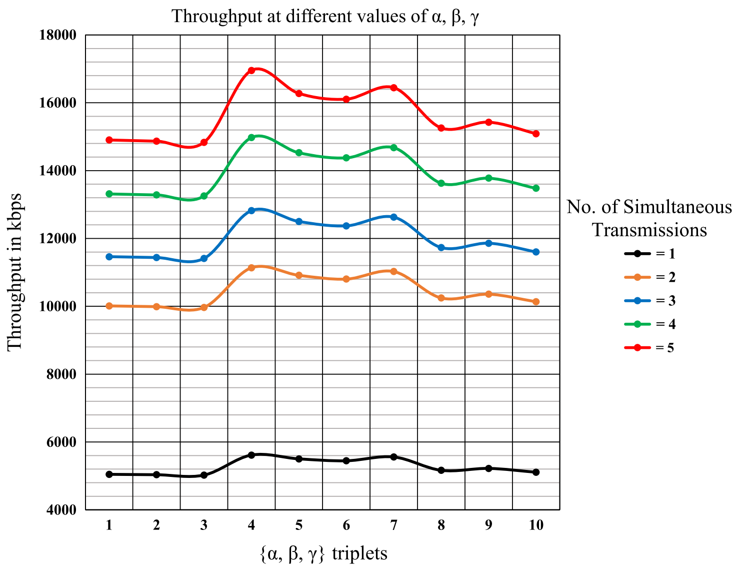


Fig. 9. Throughput at different values of α, β and γ.

Fig. 8 is the comparison of the average packet drop rate between the three protocols at decreasing traffic load. The network traffic decreases as the time interval between two successive packets increases. The graph shows the proposed protocol has the lesser packet drop rate.

Fig. 9 shows the throughput calculation of the network for different α, β, γ values as in Table 3. The simulation is carried out by increasing the number of simultaneous transmissions. If there are less number of transmissions, then the curve is almost becoming a straight line, i.e., changes in the values for α, β and γ does not make much difference in the network performance. But, as the number of simultaneous transmissions increases, there is a significant change in the throughput. From the figure it can be inferred that the curves have the peak value at fourth α, β, γ triplet. That is if $\alpha = 1/3$, $\beta = 1/3$, and $\gamma = 1/3$, the network throughput is more compared with other triplets.

Fig. 10 shows the comparison of packet delivery ratio. From the figure, it is clear that packet delivery ratio is comparatively high and almost same when the number of simultaneous transmissions is equal to one and two. Throughput depends on the network traffic, and hence throughput is doubled for these two curves in Fig. 9 because the number of simultaneous transmissions doubled and the packet delivery ratio is almost same. As the number of simultaneous transmissions increases, packet delivery ratio decreases. Then throughput will not get increased with the corresponding magnitude, so other curves in Fig. 9 are comparatively near to each other. In all the cases, peak value along the curve is at the fourth triplet.

Fig. 11 shows the average end to end delay at different values of α, β and γ. As network traffic increases, there is more congestion at the relay nodes which induces high delay for the packets. Interference would be high when more nodes try to transmit at the same time which results in more back-offs in the contention process for the medium access. So, all the components of PCF of the proposed algorithm have to have equal influence in the relay node selection. End to end delay for

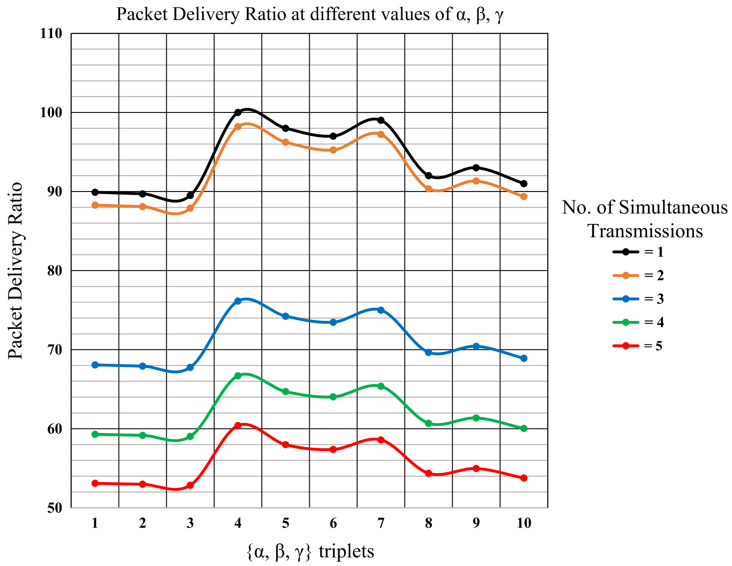


Fig. 10. Packet delivery ratio at different values of α, β and γ.

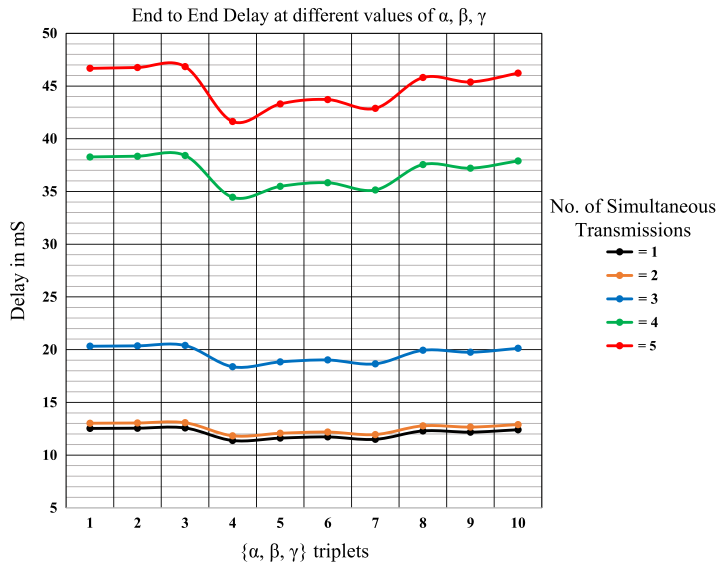


Fig. 11. End to end delay at different values of α, β and γ.

Table 3
$\{\alpha, \beta, \gamma\}$ triplets.

Triplet	α	β	γ
1	0	0	1
2	1	0	0
3	0	1	0
4	1/3	1/3	1/3
5	1/2	1/4	1/4
6	1/4	1/2	1/4
7	1/4	1/4	1/2
8	0	1/2	1/2
9	1/2	0	1/2
10	1/2	1/2	0

the packet would have the lowest value when the delay at the intermediate nodes due to congestion, back-offs, and path disconnection is reduced with suitable relay node selection. Hence, each curve in the figure has troughs at the fourth triplet.

5. Conclusion

Since the nodes in the sensor networks are using the wireless communication medium and radio transceivers to send and receive the packets, it is contingent to make interference in high traffic IoT application scenarios. That means the protocol designs should consider the link quality and the possible interference and the noise level before selecting a next hop node for communication. So the SINR factor is used in the routing choice selection process in the proposed energy efficient routing protocol. The algorithm is designed to work in the environments with heavy traffic, and high interference on the link between the nodes. Congestion level of the nodes and the survivability factor of the paths are also the deciding factors for the routing choice. The simulated results are showing that the new protocol works better well than the existing algorithm for the networks with high traffic. It has high packet reception rate, decreased end-to-end delay, and also lesser energy consumption. When the network traffic is changed by varying the time interval between the packets sent by the source nodes, the proposed protocol has 20% lesser packet drop rate. Compared to the directed diffusion, it has 14% increase in the network throughput and 29% lower end to end delay when 10% of the total number of nodes in the topology is the source nodes. Simulation results suggest that the proposed protocol works as a better routing technique in the network topologies with substantial channel interference and congestion because of the high traffic. It increases the survivability of the network and maintains the connectivity by choosing more durable paths as the routing choices. Protocols at different layers of the protocol stack have to be modeled jointly to make it works better in IoT scenarios. In the future work, this protocol would be extended with mac layer designs with transmission power control schemes and traffic adaptive dynamic contention window to have a cross-layer design.

References

[1] J.A. Gutierrez, E.H. Callaway, R.L. Barrett, Low-rate wireless personal area networks: enabling wireless sensors with IEEE 802.15. 4, IEEE Standards Association, 2004.

[2] L. Atzori, A. Iera, G. Morabito, The internet of things: A survey, Comput. Netw. 54 (15) (2010) 2787–2805.

[3] L. Atzori, A. Iera, G. Morabito, Morabito, Understanding the internet of things: definition, potentials, and societal role of a fast evolving paradigm, Ad Hoc Netw. 56 (2017) 122–140.

[4] W. Dargie, C. Poellabauer, Network layer, Fundamentals of Wireless Sensor Networks: theory and practice, 2010, pp. 163–204.

[5] A.B. Bagula, D. Djenouri, E. Karbab, On the relevance of using interference and service differentiation routing in the internet-of-things, in: Internet of Things, Smart Spaces, and Next Generation Networking, Springer, 2013, pp. 25–35.

[6] L. Catarinucci, D. De Donno, L. Mainetti, L. Palano, L. Patrono, M.L. Stefanizzi, L. Tarricone, An iot-aware architecture for smart healthcare systems, IEEE Internet Things J. 2 (6) (2015) 515–526.

[7] Y.-M. Huang, M.-Y. Hsieh, H.-C. Chao, S.-H. Hung, J.H. Park, Pervasive, secure access to a hierarchical sensor-based healthcare monitoring architecture in wireless heterogeneous networks, IEEE J. Sel. Areas Commun. 27 (4) (2009).

[8] F. Touati, R. Tabish, A.B. Mnaouer, Towards u-health: an indoor 6lowpan based platform for real-time healthcare monitoring, in: Wireless and Mobile Networking Conference (WMNC), 2013 6th Joint IFIP, IEEE, 2013, pp. 1–4.

[9] S. Misra, V. Tiwari, M.S. Obaidat, Lacas: learning automata-based congestion avoidance scheme for healthcare wireless sensor networks, IEEE J. Sel. Areas Commun. 27 (4) (2009).

[10] W.R. Heinzelman, J. Kulik, H. Balakrishnan, Adaptive protocols for information dissemination in wireless sensor networks, in: Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking, ACM, 1999, pp. 174–185.

[11] J. Kulik, W. Heinzelman, H. Balakrishnan, Negotiation-based protocols for disseminating information in wireless sensor networks, Wirel. Netw. 8 (2/3) (2002) 169–185.

[12] C. Intanagonwiwat, R. Govindan, D. Estrin, Directed diffusion: a scalable and robust communication paradigm for sensor networks, in: Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, ACM, 2000, pp. 56–67.

[13] W.B. Heinzelman, A.P. Chandrakasan, H. Balakrishnan, An application-specific protocol architecture for wireless microsensor networks, IEEE Trans. Wireless Commun. 1 (4) (2002) 660–670.

[14] S. Chinara, S.K. Rath, A survey on one-hop clustering algorithms in mobile ad hoc networks, J. Netw. Syst. Manage. 17 (1–2) (2009) 183–207.

[15] R.C. Shah, J.M. Rabaey, Energy aware routing for low energy ad hoc sensor networks, in: Wireless Communications and Networking Conference, 2002. WCNC2002. 2002 IEEE, Vol. 1, IEEE, 2002, pp. 350–355.

[16] D. Sun, X. Huang, Y. Liu, H. Zhong, Predictable energy aware routing based on dynamic game theory in wireless sensor networks, Comput. Electr. Eng. 39 (6) (2013) 1601–1608.

[17] M.J. Hossain, O. Chae, M. Mamun-Or-Rashid, C.S. Hong, Cost-effective maximum lifetime routing protocol for wireless sensor networks, in: Telecommunications, 2005. Advanced Industrial Conference on Telecommunications/Service Assurance with Partial and Intermittent Resources Conference/E-Learning on Telecommunications Workshop. Aict/Sapir/Elete 2005. Proceedings, IEEE, 2005, pp. 314–319.

[18] T. Winter, P. Thubert, T. Clausen, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, J. Vasseur, Rpl: Ipv6 routing protocol for low power and lossy networks, rfc 6550, IETF ROLL WG, Tech. Rep.

[19] M. Di Francesco, G. Anastasi, M. Conti, S.K. Das, V. Neri, Reliability and energy-efficiency in ieee 802.15. 4/zigbee sensor networks: an adaptive and cross-layer approach, IEEE J. Sel. Areas Commun. 29 (8) (2011) 1508–1524.

[20] J. Luo, J. Hu, D. Wu, R. Li, Opportunistic routing algorithm for relay node selection in wireless sensor networks, IEEE Trans. Ind. Inf. 11 (1) (2015) 112–121.

[21] Z. Wang, J. Zhang, Interference aware multipath routing protocol for wireless sensor networks, in: GLOBECOM Workshops (GC Wkshps), 2010 IEEE, IEEE, 2010, pp. 1696–1700.

[22] R.R. Rout, S.K. Ghosh, S. Chakrabarti, Co-operative routing for wireless sensor networks using network coding, IET Wirel. Sensor Syst. 2 (2) (2012) 75–85.

[23] A.M. Ahmed, R. Paulus, Congestion detection technique for multipath routing and load balancing in wsn, Wirel. Netw. (2016) 1–8.

[24] L. Ngqakaza, A. Bagula, Least path interference beaconing protocol (libp): A frugal routing protocol for the internet-of-things, in: International Conference on Wired/Wireless Internet Communications, Springer, 2014, pp. 148–161.
[25] S.K. Gupta, P. Kuila, P.K. Jana, Energy efficient multipath routing for wireless sensor networks: A genetic algorithm approach, in: 2016 International Conference on Advances in Computing, Communications and Informatics, (ICACCI), IEEE, 2016, pp. 1735–1740.
[26] L. Tang, S. Feng, J. Hao, X. Zhao, Energy-efficient routing algorithm based on multiple criteria decision making for wireless sensor networks, Wirel. Pers. Commun. 80 (1) (2015) 97–115.
[27] R. Feng, T. Li, Y. Wu, N. Yu, Reliable routing in wireless sensor networks based on coalitional game theory, IET Commun. 10 (9) (2016) 1027–1034.
[28] A.A. Youssif, A.Z. Ghalwash, Energy aware and adaptive cross layer scheme for video transmission over wireless sensor networks.
[29] H. Wang, N. Agoulmine, M. Ma, Y. Jin, Network lifetime optimization in wireless sensor networks, IEEE J. Sel. Areas Commun. 28 (7) (2010) 1127–1137.
[30] S. Boulfekhar, M. Benmohammed, A novel energy efficient and lifetime maximization routing protocol in wireless sensor networks, Wirel. Pers. Commun. 72 (2) (2013) 1333–1349.
[31] M. Tao, D. Lu, J. Yang, An adaptive energy-aware multi-path routing protocol with load balance for wireless sensor networks, Wirel. Pers. Commun. 63 (4) (2012) 823–846.
[32] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, in: Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, IEEE, 2000, pp. 10–pp.
[33] T.-Y. Chen, H.-W. Wei, C.-R. Lee, F.-N. Huang, T.-S. HSU, W.-K. Shih, Energy efficient geographic routing algorithms in wireless sensor network, J. Interconnect. Netw. 14 (01) (2013) 1350001.