© 2017 IJEDR | Volume 5, Issue 2 | ISSN: 2321-9939

A Review on Routing Protocols for Energy Harvesting Wireless Sensor Network

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***Abstract*— In traditional wireless sensor networks (WSNs), the power supply is a limiting factor on the lifetime of sensor nodes. Routing in WSNs plays a significant role in the field of environment-oriented monitoring, traffic monitoring, etc. A new class of WSN with the ability of harvesting environment power; is providing in recent decades. Energy harvesting technology has made it possible to develop independent WSNs with theoretical unlimited lifetimes. A well-designed energy-efficient routing protocol is an essential part for prolonging the lifetime of wireless sensor networks (WSNs) because a sensor node usually has limited energy. Many research efforts have contributed on routing design in WSNs. With the development of green technology, the energy harvesting technique is being applied to WSNs. Therefore, existing routing protocols are suitable for such new WSNs with energy harvesting. In this paper, we review on designing a routing protocol which takes energy harvesting as one major factor into routing design to improve the network lifetime as well as throughput. The analysis of chosen algorithms in the case of different scenarios is reviewed in this paper.**

***Index Terms*— sensor network, routing protocol, energy harvesting, energy sustainability, network lifetime, throughput**

I. INTRODUCTION

Wireless sensors are widely used in applications such as field monitoring and target tracking [1]. These sensors can gather information sensed from the ambient environment and transmit/receive information to/from neighboring sensors. By forming networks using large amount of sensors, information gathered by these sensors can be routed to one or more destinations to be further analyzed. Wireless Sensor Networks have played a major role in the research field of multi-hop wireless networks as enablers of applications ranging from environmental and structural monitoring to border security and human health control. Research within this field has covered a wide spectrum of topics, leading to advances in node hardware, protocol stack design, localization and tracking techniques and energy management [2].

Additionally, sensor nodes have limited storage capacity and batteries. And they are deployed in an ad-hoc manner and cooperate with each other to form a wireless sensor network [3],[4]. Since the communication range of sensor nodes is limited, they often adopt hop-by-hop communication to exchange data. Typically, a powerful base station, known as a sink, is also an integral part of a WSN [5]. Traditional wireless sensor nodes are powered by non-chargeable battery and may die when battery runs out. Hence, energy efficiency becomes crucial for the design of battery-powered WSNs with restricted energy. Although much more prior efforts have been paid on this subject, the network lifetime still remains as one of the key issues for design of battery-powered WSNs [6].

Recently, researchers have taken nodes which can harvest from the environment into consideration. Solar, radiofrequency or thermoelectric technologies are shown to be possible for energy harvesting [7], which can significantly extend lifetime of WSNs. This type of WSN is referred as energy-harvesting wireless sensor networks (EH-WSNs).

Energy Harvesting-based WSNs are the result of endowing WSN nodes with the capability of extracting energy from the surrounding environment. Energy harvesting can exploit different sources of energy, such as solar power, wind, mechanical vibrations, temperature variations, magnetic fields, etc. Continuously providing energy, and storing it for future use, energy harvesting subsystems enable WSN nodes to last potentially forever.

In EH-WSN, routing is a very important task that is to be handled carefully. Routing technique is needed for sending the data between the sensor nodes and the base stations, so as to establish communication. The main criterion is about the routing protocol that varies based on the application. The routing problem leads to decreased network lifetime with increased energy consumption. So, various routing protocols have been developed to minimize the energy consumption and to maximize the network lifetime.

The routing protocols can be categorized based on the nodes' participation, clustering protocols, mode of functioning and network structure. The various challenges in routing include energy consumption, node deployment, scalability, connectivity, coverage, security [9].

The organization of the paper is as follows. Section 2 describes system model, followed by the related work of the traditional routing protocols for WSN and energy harvested based WSN routing protocols in section 3 followed by Conclusion in the end.

II. SYSTEM MODEL

In the following, we introduce the system model of an energy harvesting wireless sensor network. For this, we adopt common modeling assumptions that have been used in related literature also. In particular, the models of the network structure, the energy generation/consumption and the workload within a sensor network is presented.

A. Network Model

The network consists of one single base station and any number of sensors and routers. Sensors are able to sense a physical quantity, create data packets as well as receive and transmit them. Routers cannot sense the environment and do only forward data packets. All packets in the network are routed in a multi-hop fashion to the base station. This means that the path from the sensor to the base station consists of one or multiple edges. The vertices $v \in V$ represent the nodes (i.e., the sensors, routers and the base station). An edge $< u, v > \in E$ represents a wireless link between the two nodes, $v \in V$, which allows them to exchange packets.

Taking into account that there is an edge between two nodes they can send a packet in that channel. Each node is commented with available power. Here packet energies are associated with edges even if they represent the energy spent by source nodes.

B. Energy Model

Several technologies have been discussed for harvesting energy from a node's physical environment, e.g., solar, thermal, kinetic and vibration energy. Moreover, several prototypes have been presented which demonstrate both feasibility and usefulness of sensors nodes.

The routing algorithm should be aware about the concept of packet energy(pE) which is the amount of energy used by each node to process a packet. It should be also aware of available power(AE), which shows the amount of available power in each node. Packet energy contains all the needed energy for producing, processing and directing packet in a path. Both producing and processing, can be constant value, but transmitting energy is related to the distance between source and destination. In fact there is a quadratic relation between distance and the amount of power consumption, $pE = pE0 + PE1 * d^2$, as explained in [13].

Consider that packet energy is not the only power used in WSN. There is also power usage in idle time, wait to receive events or listening for incoming packets.

C. Workload Model

Sensor networks can be used either for monitoring, that entails periodic sampling of some physical quantities, or for event detection, that entails reaction to specific events and notification of their occurrence.

In this paper, it is focused on monitoring applications based on continuous data delivery: Sensors periodically sense a physical quantity and send sampled data to base stations. In particular, the delivery model is called uniform monitoring if all sensors are required to provide data packets at the same rate [13]. For uniform monitoring, the global workload specification can be expressed by the sampling rate imposed to all sensor nodes. The local workload imposed by the routing protocol is represented by the packet rate (or flow) across each edge in the network.

To evaluate the optimal routing algorithm we have examined the Maximum Energetically Sustainable Workload $(MESW)$ of a given routing algorithm, which represent a workload that can be energetically sustainable in a given routing algorithm [8].

To evaluate how much the packet energy can be sustained with the environmental power, recovery time(T_e) is denoted. This is the time required by each node to harvest an amount of energy that is used to receive and transmit a packet through a path. As a result the following relation exists between environmental power (P_n) and packet energy (Packet energy (pE_e)).

$$T_e = \frac{pE_e}{E_n} \qquad (1)$$

Another main quantity is Channel capacity C_e, which is the maximum packet rate across an edge. The channel capacity has an inverse relation with recovery time. It means as much as the time for receiving energy increase, the maximum rate decrease.

$$C_e = \frac{1}{T_e} \qquad (2)$$

The flow F_e across edge e is limited by its energetically sustainable channel capacity, expressed by:

$$F_e \le C_e = \frac{1}{T_e} = \frac{P_n}{pE_e} \qquad (3)$$

This networks with constrained edges to a given channel capacity are called flow network.

III. RELATED WORK

We briefly review related works on traditional routing protocols and energy harvesting based routing protocols for WSN.

A. Traditional Routing Protocols

Based on the network topology, routing protocols for WSNs can be classified as following three categories, flat routing, cluster-based routing and location-based routing.

In multi-hop flat routing protocols, each of the nodes plays the same role to transmit data to neighboring nodes. Data reach the sink node in the end. However, energy is wasted when the duplicated data are transferred to the sink node through different routes.

In a hierarchical architecture, lower energy nodes are used to sense in the proximity of the target and higher energy nodes are used to process and send the information. The higher energy nodes are selected as cluster heads. They greatly contribute to overall system scalability, lifetime, and energy efficiency. Cluster-based routing performs data aggregation and fusion in order to decrease the number of transmitted messages to the BS. It is an efficient way to lower energy consumption. However, other indicators such as throughput, data failure rate are not so good using cluster-based routing.

In location-based routing, the distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Nodes should go to sleep if there is no activity to save energy. The problem of designing sleep period schedules for each node in a localized manner was addressed in [11], [12].

B. Energy Harvesting Routing Protocols

The aim of EH-WSN routing algorithm is to increase the throughput with increasing network lifetime. But for some algorithms of this category, the concept of sustainability is also considered [13]. Sustainability means that each node should not consume more energy than the energy it can harvest over a period of time.

In this section it is tried to collect all the information present in literature about routing algorithms in EH-WSN, and it is discussed about how to evaluate the sustainability of algorithms.

Randomized Max-Flow

Lattanzi et al. presented in [13] an extended version of the Ford-Fulkerson algorithm that calculates the maximum flow from the sensors to the base station. It is used to create the Randomized Max-Flow (R-MF) algorithm. The algorithm uses the pre-calculated maximum flow over the edges to determine the route of a packet. The probability to route a packet over an edge is proportional to the maximum flow through that edge.
Each edge is assigned with:

$$Capacity = \frac{harvesting\ \ rate\ \ of\ \ the\ transmitter}{packet\ \ energy} \quad (4)$$

This routing algorithm is based on using an off-line routing table, stored in each node that shows the node links used for packet transmission.

Energy-opportunistic Weighted Minimum Energy Max-Flow

This routing algorithm provides energy aware framework with energy replenishment. It tries to use the important part of two following routing algorithm. Algorithm 'ME' tries to achieve a minimum energy routing and algorithm 'max-min', tries to choose a node with high residual energy. Most of the EH-WSN protocols for routing use the residual energy, meanwhile E-WME uses both residual energy and the replenishment rate of the transmitter.

Lin et al. introduced in [14] the Energy-opportunistic Weighted Minimum Energy (E-WME) algorithm. The algorithm is defined for each node u the cost c_u which depends on the available energy,$E_{C,u}$, the battery capacity $E_{M,u}$, the harvesting power rate p_u and the reception and transmission energy. The algorithm calculates the shortest path from the source to the destination with respect to this node cost. The cost c_u at node u is given as:

$$c_u = \frac{E_{M,u}}{(p_u+\epsilon).\log(\mu)}(\mu^{\lambda_u} - 1)e^{u,v}_{routing} \quad (5)$$

where $e^{u,v}_{routing}$ is the energy needed to receive a packet and transmit it to the downstream neighbor node v. The constants, ϵ and μ have to be chosen appropriately. The power depletion index λ_u is defined as:

$$\lambda_u = \frac{E_{M,u} - E_{C,u}}{E_{M,u}} \quad (6)$$

where $E_{C,u}$ is the available energy at node u right before processing the packet and $E_{M,u}$ is the battery capacity.

Randomized Minimum Path Recovery Time

Selection of routes is performed at each node based on energetic sustainability information. The algorithm works exactly as the previous one, but cumulative recovery time is computed for each path $RTpath$ instead of path energy. $RTpath$ is 0 at the base station. During interest propagation, when node n receives an interest from edge i, it updates $RTpath$ by adding the recovery time of edge i and stores the result in the i-th entry of the routing table: $RTpath_i = RTpath + pEi/Pi$. During data propagation, the probability of sending a packet through an edge is inversely proportional to the corresponding path recovery time [14].

Here the cost function is defined as:

$$cost = \frac{Packet\ \ energy}{Harvesting\ \ rate\ of\ the\ transmitter} \quad (7)$$

Randomized Minimum Path Energy

This algorithm works based on the minimum energy required to reach the sink [14]. Path energy information ($Epath$) is sent downward within a message and stored in the local routing table of each node. This information propagation starts from the base station which has $Epath$ equal to zero. When the message reach a node n, from edge i, it updates the packet energy required by that edge in the routing table: $Epath_i = Epath + pEi$.

The probability of sending packet from an edge is inversely related to the corresponding path energy.

Energy Harvesting Opportunistic Routing Protocol

Zhi et al. [15] proposed opportunistic routing protocol for multi-hop WSN-HEAP (powered by ambient energy harvesting). This algorithm uses opportunistic retransmission; it means that in the routing if one node fails, another node can be used for transmitting data packet.

In WSN-HEAP, there is the energy-harvesting device that converts ambient energy to electrical energy. Also there is energy storage device, which it stores the energy, has been harvested from the environmental. When enough energy is harvested the transmitter starts to work and continuously broadcast data packet till the energy finish. Then it will turn off. This process repeats again in the next cycle.

There are three possible phases for each node such as charge phase, transmitting or receiving phase. In a network with n region, any node has n-1 receiving time slots for each region and 1 transmission time slot. When node charges with enough energy, it is ready to participate in receiving packet. If it receives a packet in any of its time slots, it can distinguish the region which packet came from. Then if the region is further from the sink than its own region, it caches the data and waits till reach its own transmitting time slot. In transmitting time, it chooses the next region with considering their priority for forwarding, in base of distance to sink and have enough energy. Then it will start to transmit.

Energy Ability Greedy Perimeter Stateless Routing for Wireless Networks

Shuo Yi et al. [16] propose the Energy Ability algorithm to measure a node's ability of harvesting energy and its residual energy state. Variables of a node are defined as follows: R_k, the residual energy of node k; H_k, the energy node k will harvest in the next unit of time.

EA algorithm is defined as follows:

$$F_k = \frac{e^{\lambda_r(R_k-\mu_r)} + e^{\beta\lambda_h(H_k-\mu_h)}}{1+e^{\alpha\lambda_r(R_k-\mu_r)} + e^{\beta\lambda_h(H_k-\mu_h)}} \quad (8)$$

where $R_k - \mu_r$ is used to measure the state of residual energy and $H_k - \mu_h$ is used to measure the ability of harvesting energy. μ_r, μ_h, λr and λh are parameters used to standardize. The definitions of them are as follows:

$$\mu_r = E(R_k) \quad (9)$$

$$\mu_h = E(H_k) \quad (10)$$

$$\lambda_r = \frac{1}{\sqrt{Var(R_k)}} \quad (11)$$

$$\lambda_h = \frac{1}{\sqrt{Var(H_k)}} \quad (12)$$

α is the adjust parameter of residual energy, β is the adjust parameter of harvesting energy.

When choosing neighbour nodes as the next hop, EA-GPSR takes full consideration of a node's location, residual energy and energy harvesting ability.

Energy Harvesting Routing

This paper introduces a hybrid routing metric combining the effect of residual energy and energy harvesting rate [17]. Then an updating mechanism is proposed allowing every node to maintain dynamic energy information of its neighbors. Based on the hybrid metric and the neighbor information, EHR is able to locally select the optimal next hop.

There are four phases in the EHR algorithm. The phases are as follows:

a) Information initialization: When a WSN begins to work, each node initializes its information in routing table. Information in Neighbor Table is attained by transmission.

b) Dividing energy levels: In this phase, the EHR algorithm computes each node's level. The source node only transmits data to nodes with $Li = Lmax$.

c) Next hop selection: Each source node selects the node to forward data in this phase. All its neighbors will receive the data packet. However, only the selected node will accept and decode it.

d) Updating information: A time-slot is proposed based on information-updating mechanism to update the table efficiently with little overhead.

IV. CONCLUSION

In the previous section, the protocols from literature are analyzed. They are based on energy harvesting paradigm. By doing survey on the energy-efficient routing algorithms category; it has been clear that common aim in these techniques is to extend the lifetime of the sensor network without compromising on data delivery. Different analysis metrics could be evaluated by means of different scenario simulation. For instance in the scenario of different number of node with increasing the number of nodes the throughput and collision rate increase. Selecting the best routing protocol in context with energy harvesting is challenging in the field of WSN. And the selection depends upon different parameters. Hence various algorithms have been discussed in this paper. The future challenges include security routing, energy demand and multi objective routing.

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