

Energy Efficient Routing Protocols and Introduction to Wireless Recharging of Sensor Nodes in Wireless Sensor Networks

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Abstract—This paper gives a brief review of the concept of sensor networks which has become feasible due to large scale development in micro electro-mechanical systems technology and wireless communications. First of all, sensor node deployment and sensor networks applications are presented, and then various issues regarding sensor node lifetime are discussed. Then, to solve sensor node issues, various energy conservation techniques, their advantages and limitations are discussed. The energy conservation techniques are compared using MATLAB and best routing protocol is shown. Lastly, wireless power transfer to replenish sensor node battery is discussed. A review of wireless power transfer history and various development in this technology is also given to solve the energy issue of sensor node. Research issues for efficiency improvement of wireless sensor network are also discussed.

Keywords— Wireless sensor network (WSN), energy conservation, wireless energy transfer, Routing, energy harvesting.

I. INTRODUCTION

The recent development in wireless communication has enabled scientists to develop a low cost and multi-functional sensor node. These sensor nodes consist of various components and work in a combined manner to sense and forward data from surroundings [1]. These sensors can be deployed in the surrounding areas through various methods [1], [3]. A huge number of sensor nodes when joined together form a sensor network. After sensing data from physical environment, these sensors forward data to a sink node. The sensed data is converted into signals and forwarded to a processing unit to reveal the characteristics of the area surrounded by the WSN.

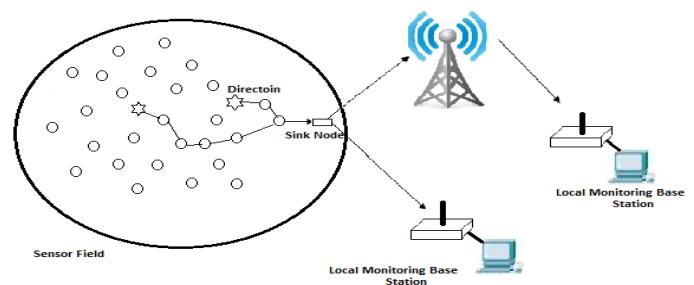


Figure 1: Deployment of sensor nodes in a sensor field

Figure 1, [1] shows deployment of nodes in a sensor field. Sensor nodes are generally deployed in remote areas. They must possess self-organizing technique and work in combine manner. In this way sensor differentiates the required data from surrounding noise and forwards it. Sensor networks have wide range of applications which include indoor, battlefield, underwater, e-health etc. [1], [3], [4]. To get a better understanding of these applications, we need to know about wireless ad-hoc networking. The various differences between sensor and ad-hoc networks are defined in [1], [3] as:

- Number of nodes in sensor network is greater than ad-hoc network.
- Sensor network is more stable than ad-hoc network.
- Broadcasting technique is used by sensor nodes while ad-hoc uses point-to-point communication.
- There is power constrain in case of sensor nodes.

Since sensor nodes are very large in number and placed closed to each other, multi-hop communication is considered better for data transmission [1]. Also, sensor nodes have limited battery life and generally placed in remote areas where manual battery replacement is impossible, so priority should be power conservation for sensor nodes.

A lot of papers have been proposed to tackle the issue and still a lot of research is being done on the problem. In this paper we have a look on various protocols which have been proposed for energy conservation. We also survey various techniques used for sensor battery recharging from outside. We try both of the

techniques and try to figure out which one is better in all conditions. The rest of the paper is organized as follows: Section II shows the application of sensor nodes, section III shows energy conservation, section IV results, section V wireless recharging techniques while section VI concludes the paper.

II. APPLICATIONS OF SENSOR NODES:

Different types of sensors are described in [1] like thermal, infrared, seismic, acoustic, low sampling rate and visual which can monitor data in every type of harsh environments. These sensors can monitor various factors like motion of vehicles, smart grid, pressure, temperature, noise level, humidity etc. We can divide these applications into various categories like battle field, e-health, indoor, underwater and several other categories [1].

A. Battlefield Applications

WSN can be necessary part of military command and control, surveillance, computing, targeting systems, intelligence etc. To increase military capabilities, a large number of sensor data analyses can be connected. So WSN have become a vital part of military information system. Sensors are used for targeting, battlefield surveillance, damage estimation, checking opposite forces movement and monitoring friendly forces equipment [1].

B. Indoor Applications

Nowadays humans are depending upon sensors for indoor applications too. A wide range of sensors have been deployed inside smart home for various applications. Some of the major uses of sensors are to switch on or switch off the light or TV, boil water and eggs, open the door, prevent theft cases, heating, air conditioning and ventilation. They also take good care of elderly people who otherwise need care taker for their necessities. Sensor deployed in smart home can also detect smoke and alert passersby or call the fire department automatically [1].

C. E-health Applications

Health applications of sensor nodes includes helping the disabled patients, drug administration inside hospitals, locating the exact position of patients and hospital staff while on duty, monitoring and diagnostics of patients and tele-monitoring human psychological data [2].

D. Environmental Applications

Some of the environmental application of sensors includes detecting forest fire and flood, tracking the movement of migratory birds and small insects, Irrigation, Pollution study, chemical and biological detection and monitoring various conditions that effects crops and livestock [3].

E. Issues restricting WSNs

The main issue encountered by WSN is Routing. It is complicated in WSN because of limited battery lifetime, no conventional addressing scheme, self-organization and limited transmission range, dynamic nature of nodes and computational overhead. A sensor generally has limited lifetime and cannot be easily replaced due to remoteness of deployed area. The initial capacity of battery plays a vital role in lifetime of sensor node.

Routing, power issues, security and random topology are the main limitations faced by WSN [1].

III. ENERGY CONSERVATION OF WSNs

As we all know that routing is the main issue faced by WSN due to several factors [2]. The factors include limited power supply, non-applicability of IP to WSNs, limited resources, abundance of data collected by WSN, data collection must be in form of multiple inputs to single output and finally data must be collected in specific time. According to [2], energy conservation has more priority over quality of service as it is related to network lifetime. Routing can be flat or hierarchical with flat having nodes performing same tasks and hierarchical having nodes performing different tasks. We are more focused on hierarchical in which cluster are generally formed for data transmission and energy conservation. A brief survey of cluster-based routing protocol is presented in [2],[5],[6],[7],[8] which describes two steps in cluster formation. The cluster head selection and data transmission. Routing through cluster formation has several advantages like less energy consumption, scalability, data aggregation, less load and more robustness, fault tolerance, guarantee of connectivity, Avoidance of energy hole and quality of service. The cluster head can be predetermined and fixed or can be selected randomly. Similarly, the cluster head may be stationary or mobile. The clustering scheme may be homogeneous or heterogeneous based on energy of the sensor nodes. Also, the clustering may be centralized, distributed or hybrid based on control manners. Similarly, the clustering may be proactive, reactive or hybrid depending on the proactivity of clustering routing [2]. We are going to explain different cluster-based routing protocols with their advantages and deficiencies in order to have a better understanding of the concept. A brief explanation of those cluster-based protocols is stated in the following portion.

A) Low Energy Adaptive Clustering Hierarchy (LEACH);

The pioneer in clustering routing protocols for WSNs is LEACH [2], [5], [6], [7], [8], [9]. Its main advantage is load balancing which is achieved by cluster formation. One node act as the head of the cluster which is responsible for collecting data and transmitting it to the base station. Usually the node with maximum energy left acts as cluster head for one round and then each node in the cluster takes its turn to become cluster head. The cluster head fuses data of its own and other nodes and sends a single fused data to the base station [9]. For cluster head selection, certain probability is seen. The communication energy should be minimum between participating nodes and the cluster head. Data transmission within a cluster is done through a fixed schedule and the nodes should be in sleep condition for the remaining time to save the battery power.

When clustering starts, a node selects a random number between 0 and 1. If the number is less than a fixed threshold $T(n)$, node will be cluster head for the current round which is then broadcasted within the cluster. The threshold is determined as:

$$T(n) = \begin{cases} \frac{p}{1-p * (r \bmod \frac{1}{p})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases}$$

G represents nodes which were not cluster head in last rounds, p is percentages of cluster head and r is current round.

The advantage [2] of LEACH is that it is fully distributive and do not requires information about global network, node serves as CH once in a round, unnecessary collisions are prevented and excessive dissipation of energy is prevented. Some of the deficiencies of LEACH are given single hop communication, lack of real load balancing and extra overhead due to dynamic clustering.

B) Distributed Energy Efficient Cluster Formation Protocol (DEEC):

In DEEC [10], the energy is distributed without having known the entire network. The network lifetime has an ideal value which gives us the amount of energy for each node to use in a single round. The cluster head selection again depends upon probability which is ratio of energy of the whole cluster to the energy of a single node. So, nodes with more energy left, become cluster head. It works better in an environment having different energy levels. The initial energy of the network is described by following equation:

$$E_{total} = \sum_{i=1}^N E_o(1 + a_i) = E_o \left(N + \sum_{i=1}^N a_i \right)$$

For cluster head selection, let n_i is the number of rounds for becoming cluster head for the node s_i . For heterogeneous environment, the node having higher energy left has more probability p_i . The threshold for cluster head selection is given as:

$$T(s_i) = \begin{cases} \frac{p_i}{1 - p_i(r \bmod \frac{1}{p_i})} & \text{if } s_i \in G \\ 0 & \text{otherwise} \end{cases}$$

G is number eligible nodes to become cluster head. S_i will be part of G if it was not a cluster head in recent rounds. A random number is again chosen for the range of 0 to 1 which should be less than threshold T (s_i) for a node to become cluster head.

C) Stable Election Protocol (SEP):

Stable Election Protocol (SEP) [11] increases the duration between start of operation and the point at which the first node is drained completely of energy. This protocol has knowledge of the different energy nodes in the network. Certain fixed probability is assigned to every node in the network to become cluster head. This probability depends upon energy level left in a single node to that of the whole network [11]. As the energy of nodes is not same, so n represents the network and m is its part. Let suppose two types of nodes are there in the network, one having more energy and the other having less energy. Advance nodes are the one having high energy and the remaining nodes are normal nodes. If normal nodes have energy E_o , the energy of advance nodes is little higher by a factor of $(1 + a)E_o$. The total energy of the system having different energies is represented by the equation:

$$n. (1 - m). E_o + n. m. E_o. (1 + a) = n. E_o. (1 + a. m)$$

The decision for each node to become a cluster head depends upon its remaining energy. Based on this energy, a probability is given to advance and normal nodes which is given as:

$$p_{nrm} = \frac{p_{opt}}{1 + a. m}$$

$$p_{adv} = \frac{p_{opt}}{1 + a. m} * (1 + a)$$

Also, the threshold for the advance and normal nodes is given by following equations:

$$T(S_{nrm}) = \begin{cases} \frac{p_{nrm}}{1 - p_{nrm}(r * \bmod(1/p_{nrm}))} & \text{if } S_{nrm} \in \hat{G} \\ 0 & \text{otherwise} \end{cases}$$

$$T(S_{adv}) = \begin{cases} \frac{P_{adv}}{1 - P_{adv}(r * \bmod(1/P_{adv}))} & \text{if } S_{adv} \in \ddot{G} \\ 0 & \text{otherwise} \end{cases}$$

So, by the concept of weighted probability, SEP increases the time duration before the first node is drained off energy completely. This region is called stable region which is very much greater than previous routing techniques used for the task.

D) Threshold sensitive Energy Efficient sensor Network protocol (TEEN):

In TEEN [2], [12], nodes form cluster by passing through different hierarchies. The formation is cluster head is same as explained in previous routing schemes. The main difference between TEEN and other routing techniques is that in TEEN manual setting of values for the cluster head is needed. That is why it is called reactive protocol. These values of cluster head are of two types, one is soft and the other is hard threshold. When the cluster head receives both these values manually, it sends them to all nodes. The member node regularly collect data but send it to cluster head only if it becomes greater than the value of hard threshold. So, setting hard threshold, unnecessary transmission between member node and cluster head is prevented. The cluster head stores values of the member node in a variable naming "sensed value." This sensed value is the soft threshold value and the member nodes transmit data only when their sensed data become greater than this value. The values of soft and hard threshold are changed manually when a new cluster is forming. Because of large value of high threshold, cluster head will have no information about death of member nodes in the cluster.

A few advantages of TEEN are presented in [2] which say that the transmission energy can be decreased by taking advantage of two thresholds. TEEN is more suitable for reactive and time critical applications. Some disadvantages of TEEN according to [2] include its non-efficiency for periodic reports, wasted time-slots and chance of data loss.

E) *Tree Based Routing Protocol (TRP):*

This routing protocol [13] constructs the best route between a sensor node and a base station. In TRP, a node selects another nearby node as its parent calculating the amount of energy required for communication, the distance from the neighboring nodes to the BS, and the amount of energy left in the neighboring nodes.

Tree based routing protocol works better for a phenomenon in which sensor nodes want to transmit data to BS in every round of data transmission. TRP takes advantage of data aggregation techniques in order to increase the lifetime of the network by reducing the dissipated energy during the communication process.

a) *Network Model:*

Generally, sensor nodes are dispersed randomly, BS is stationary, sensor nodes have same initial energy and location unaware, each sensor node has limited amount of energy but BS has infinite, sensor nodes can perform data fusion and can find the distance between nodes through received signal strength indication (RSSI).

b) *Tree Formation:*

Each node chooses nearby node as parent node on the basis of given criteria:

1: The parent node must have shorter distance to base station than the child node.

2: The child node must have less communication and residual energy than its parent node.

If more than two nearby nodes have same distance or number of hops to the base station, the node with the best link quality is selected as its parent. When every participating node finds its parent node, a tree rooted at the base station is formed. In tree-based topology, a node at certain level L, selects a node at the immediate lower level (L-1) as its parent. In this way the sensed data is sent to the base station.

F) *Chain Based Routing Protocol:*

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [14] is a protocol which follows chain-based technique. In PEGASIS each node collects data and transmits it to the nearby node and waits for its turn to forward the data to the base station. In PEGASIS a chain is formed among sensor nodes and each receives and transmits data to its closest node. The data gets fused and moves from one node to another until a designated node sends the data directly to the BS. In order to reduce the energy spent during transmission, all the nodes take turn to communicate with the BS. Multi-hop transmission is utilized when nodes are far away from each other's transmission range. Chain based protocol will not be affected because of communication between neighbor nodes only and multi-hop transmission can be adjusted in transmission to the BS. In case of heterogeneous environment, the remaining energy of each node is considered along with the transmission energy cost. The BS generally determines each node's location however through received signal strength nodes can determine it too.

The equations for transmission and reception of k-bit message at distance d are given as [14]:

$$E_{Tx}(k, d) = E_{Tx} - elec(k) + E_{Tx} - amp(k, d)$$

$$E_{Rx}(k) = E_{Rx} - elec(k)$$

The number of transmissions should be less as it also costs highly. Compared to LEACH [9], PEGASIS saves energy by minimizing the transmission, reception and the distance d. Furthermore, in LEACH more nodes become CH in every round and transmit fused data to BS. To save maximum energy, only one node should send data to CH and the remaining sends it to their immediate neighbors [14]. PEGASIS works on the idea that to transmit and receive data each node has to contact its immediate neighbor and has to wait for its turn to connect directly with the BS. As a result, the energy load is uniformly distributed among all the nodes. The random distributed nodes form a chain according to greedy algorithm [15]. This chain is recognized by the BS and is broadcasted over the whole network. When a node is run out of battery, it is bypassed and another chain is formed in the same manner. Leader of the chain can be at any random position. Every node fuses data of its own and its neighbor to form a single packet of data except the last one of the chains. Thus, only one packet is sent by each node in every round. It is possible that some nodes have large distance from their neighbor nodes. Such nodes cannot become leader as they dissipate more energy. To prevent this, a threshold is set on neighbor node distance. In PEGASIS the transmission distance is less than LEACH, amount of data received by leader is less and only single node transmits to the BS. In PEGASIS energy load is uniformly distributed among all nodes which increase the lifetime and quality of network. The results are better for a large network.

IV. SIMULATIONS AND RESULTS

The Hierarchical based routing protocols are compared using MATLAB simulator. 100 nodes are distributed equally in a network area of 100m * 100. The system is compared for a total of 4000 rounds. Various networks parameters are represented using following table.1.

Table 1: Network Parameters

Parameters	Values
Network Size	100m * 100m
Initial Energy (Eo)	0.5 J
Total number of nodes (n)	100
Data Aggregation Energy (EDA)	50 pJ/bit J
Data Transmitting Energy (ETX)	50 pJ/bit J
Data Receiving Energy (ERX)	50 pJ/bit J
Distance (do)	87.7058 m

Number of rounds (r)	4000
Probability (p)	0.1
Amplification Energy (Emp) when (d>do)	0.0013 pJ/bit J
Amplification Energy (Efs) when (d<do)	10 pJ/bit J

A. Dead Nodes Comparison

The dead nodes can be compared with the help of following MATLAB figure. From the figure, it is clear that DEEC outperforms all hierarchical based routing protocols because it is heterogeneous aware while others have certain limitations.

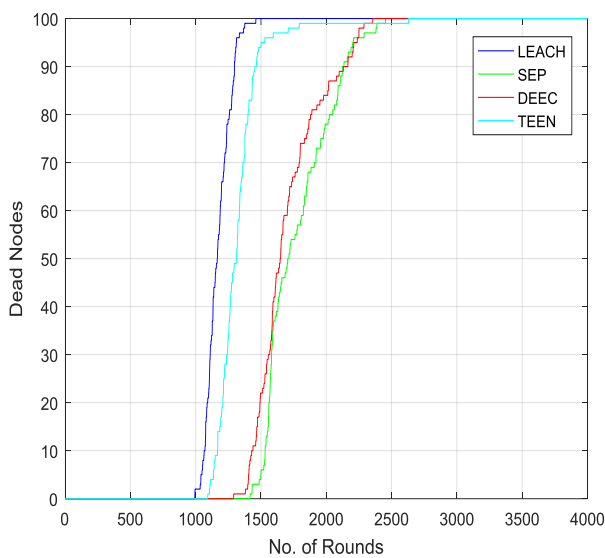


Figure 2: Comparison of dead nodes

The above figure shows the comparison of energy efficient routing protocols for dead nodes.

B. Data Packets Comparison

The total amount of data packets sent to base station can be compared using the following figure. DEEC again outperforms all the hierarchical routing protocols since it is more heterogeneous aware.

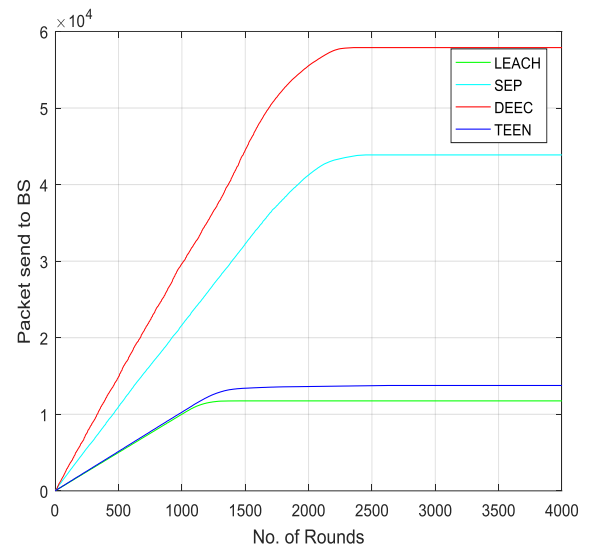


Figure 3: Total Data Packets Comparison

The total amount of data packets has been compared in the above figure.

C. Data Packets per Round Comparison

The amount of data packets sent to base station per round can be compared in the following figure. DEEC again outperforms all routing protocols.

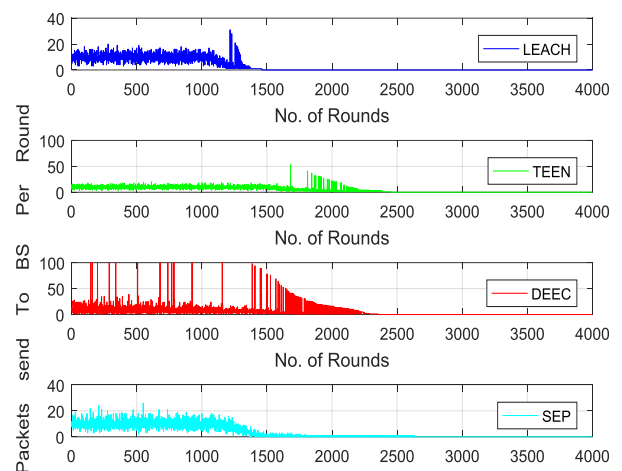


Figure 4: Data Packets sent per Round Comparison

The above figure shows the number of data packets sent per round.

V. WIRELESS RECHARGING OF SENSOR NETWORK:

Sensor nodes consist of batteries which do not last long. Several energy conservation techniques [9-14] have been proposed which are thoroughly discussed in the upper portion. However, these energy conservation techniques only slow down the energy usage process and cannot be considered as life-long processes. To tackle this issue, several energy harvesting

techniques like wind [26], solar [25] and vibration energy [27] have been proposed. These techniques have numerous advantages but they are uncontrolled and not applicable to certain harsh environments like underground vault or power line sensing, underwater monitoring and certain other environments where these energy harvesting techniques have their bottleneck. A more robust and reasonable technique is wireless recharging of these sensors manually or through robots [15], [16], [18], [19], [21]. The pioneer in wireless charging techniques is presented in [28] which have opened new ways of wireless energy transfer. The overview of wireless charging is presented by the following figure [15].

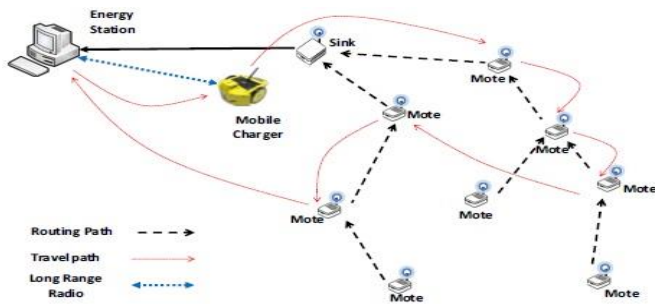


Figure 5: Overview of wireless energy transfer

The history of wireless power transfer dates back to Tesla, who tried to transmit signal and electricity wirelessly. Due to certain circumstances, Tesla's idea was not put to practical use until the use of electronic devices became popular in the 20th century. Various power transfer techniques have been proposed which will be discussed in detail in the following part.

I. Inductive Coupling:

The basic principle for inductive coupling [19] is magnetic field induction. An alternating current in the primary coil (source) produces changing magnetic field due to which a voltage is induced across secondary coil's terminals (receiver). Due to safety and simplicity, it is a good choice for wireless power transfer. Cell phone's charging pad and electric toothbrush works on inductive coupling. Although inductive coupling is pioneer technology in wireless power transfer but there are certain issues which limits its performance. It works well when the power source and destination are in close contact and aligned. Due to this limitation it does not work well in the case of wireless sensor network.

II. Magnetic Resonance Coupling:

The magnetic resonance coupling [28], [19] is based on resonant coupling principle which states that "by having magnetic resonant coils operate at the same resonance frequency so that they are strongly coupled via irradiative magnetic resonance induction" [19]. The magnetic and mechanical resonance can be considered same by giving example of a string, tuned to specific tune and can be vibrated by a sound source at a distance only if their resonance frequencies match. The energy transfer between source and receiver coil in case of resonant coupling is much efficient. An experiment was conducted to light a 60 W bulb at a distance of 2 meter in [28] was not achieve able through inductive coupling. It can be considered as enhanced form of inductive coupling that is more transfer

efficient and has high range. Magnetic resonant has some limitation like maximum distance can only be achieved if source and receiver are placed along a common axis and careful tuning is needed to prevent interference. It is more efficient, less harmful and do not requires line of line of sight between sender and receiver.

Following figure [19] shows a wireless charger vehicle which travels inside a network and wirelessly charging each sensor node based on magnetic coupling. Upon charging the whole network, the vehicle returns to its station, fills its battery and becomes ready for the next trip. The concept of renewable energy concept described fully in [19] to recharge sensor nodes in time. The magnetic resonant coupling, if rightly designed can provide life-long energy to sensor nodes. But through this technology only one sensor is charged at a time. When the network size increases, this technology becomes non-scalable.

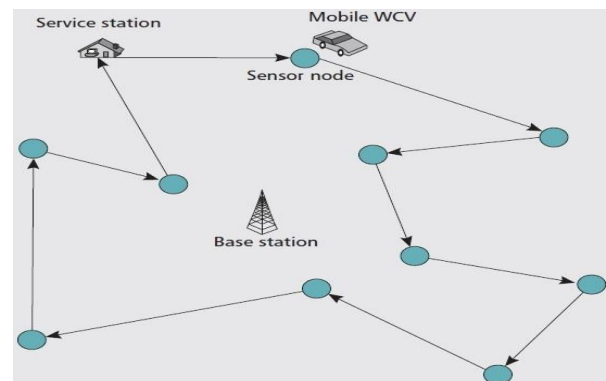


Figure 6: A mobile charge carrying vehicle charging sensor nodes

III. Electromagnetic Radiation:

Energy is transmitted between source and receiver antenna through electromagnetic waves. This type of radiation can be unidirectional or omni-directional. For omni-directional transmission a frequency range of 902 to 928 MHz is used for transmission in omni-direction while tuning the receiver to a similar frequency range. But omni-directional transmission suffers greatly with transmission distance and harmful to humans. So, it is only useful for very low power sensor nodes (up to 10mW). The unidirectional transmission is more efficient if a clear line of sight exists between transmitter and receiver. The maximum value of power for RF energy harvesting is 7 μ W and 1 μ W for a frequency range of 900 MHz to 2.4 GHz for a distance of 40m [24]. The summary of all these techniques is presented in following table [20].

Table 2: Summary of wireless recharging techniques

Wireless energy transfer technique	Field region	Propagation	Effective distance	Efficiency	Applications
RF energy transfer	Far-field	Radioactive	Depends on distance, frequency and sensitivity of energy	0.4, 18.2 and 50% at -40 dBm, 20 dBm, -5 dBm	Wireless sensor and body networks
Resonance inductive coupling	Near-field	Non-radioactive	From a few millimeters to a few centimeters	From 5.81% to 57.2% when frequency varies from 16.2	Passive RF identification tags, contactless smart cards, cell
Magnetic resonance coupling	Near-field	Non-radioactive	From a few centimeters to a few meters	From above 90% to above 30% when distance varies from 0.75m to 2.25m	PHEV charging, cell phone charging

A more inside of radio frequency RF energy harvesting is presented in [20], [21] and [24]. The wireless sensor network application to monitor chronic disease patients is presented in [23] and smart grid monitoring is presented in [21], [22]. In [21] sustainable wireless rechargeable sensor network (SuReSense) is presented which makes use of mobile wireless rechargeable robots (MICROs) to recharge the batteries of sensor nodes. Two steps are involved during operation of MICROs, one step being minimum number of landmark selections on the basis of energy requirement and location. This step is done with the help of integer linear programming. In the second step a cluster is formed from these landmarks, each being taken care of by a single MICRO. The MICRO follows shortest Hamiltonian path to serve each landmark in its cluster and transmits power wirelessly to the sensor nodes. In this way the traversed path is further reduced which enables the MICRO to pass more time at the energy source to refill its own battery. The waiting time of sensor nodes is also reduced in this manner.

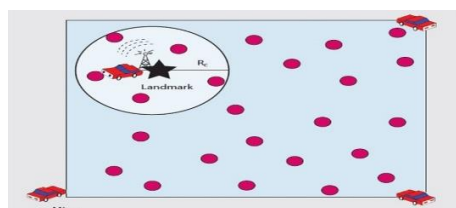


Figure 7: Cluster, Landmark and SenCar during Operation of SuReSense

The mobile charger shown in the above figure [21] is called SenCar and it consists of high capacity battery, a DC/AC converter and a resonant coil. It goes to the nodes which are deprived of battery power while collecting data in the meantime. Another RF energy harvesting technique for mobile sensor nodes is presented in [24], which makes use of Schottky diodes to implement energy harvesting. This technique is very much helpful in charging a low battery mobile device by placing it near a fully charged mobile device and draining energy to recharge it.

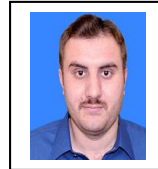
CONCLUSION

Wireless communication has become vital part of our life nowadays, playing a role in almost every field. As the sensor network is dependent on small sensors, which have limited battery life and will be of no use if the battery charge is drained. To enhance the battery life, various energy efficient protocols are proposed. But these protocols only decrease the energy expenditure by various techniques and do not last long. To have a better solution, wireless recharging of the sensor nodes is proposed. Through wireless charging, the life of sensor nodes last life-long. Three different techniques of wireless charging were proposed, the best of which was electromagnetic radiation (RF) technique. A lot of work has been done in this field but for future research combining energy efficient techniques with wireless charging of sensor nodes can increase the efficiency further. Also, wireless data gathering along with recharging can be done to improve performance i.e. the phenomenon of LEACH [9] can be combined with wireless energy transfer process. The sensor nodes chose their cluster head and only this cluster head communicates with the mobile charger. It takes charge from the mobile charger and distributes this charge among members of its cluster. In return it transmits the collected data to the mobile charger and this process goes on.

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