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DESIGN ASPECTS OF WIRELESS SENSOR NETWORKS

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Abstract—Wireless Sensor Networks (WSNs) are one of the most important and recent technologies in the 21 century that has many various applications. WSNs facilitate the interaction between humans and the environment. They attract enormous number of researchers and foundations to study and release many researches, devices and applications. In the coming years, with the rapid advances in integrated circuit design that leads to small size and low-cost chips, it is expected that there will be a great revolution in WSN applications. In this work, we analysis the important issues associated with the design and development of WSN.

Keywords—WSN, wireless sensor networks, base station, clustering.

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Introduction

A wireless sensor network (WSN) is composed of large number of densely low-cost, low-power and battery-operated sensor nodes. These nodes work collaboratively to achieve a common objective. WSN has a central unit known as sink or base-station (BS) which collects data from the sensor nodes. Base station represents the link between WSN and the outside world. Since sensor nodes have limited transmission ranges, only some of them can send data directly to the base station. Fig. 1 shows the basic components of wireless sensor network.

In most applications of WSNs, the network is deployed without a pre-defined structure and left unattended to perform multiple monitoring or tracking tasks. Thus the WSN should be able to self configure its operation and connectivity. Also WSN can integrate new nodes in the network since node failure is common in its applications [1].

A wireless sensor device is a low power battery operated device that is used to sense a physical quantity. It is capable of wireless communication, data storage, and a finite computation and signal processing capabilities. Thus sensors are a type of transducers that covert the physical quantities into electrical energy that can be processed analyzed and controlled [2]. Fig. 2 shows the architecture of a wireless sensor node.

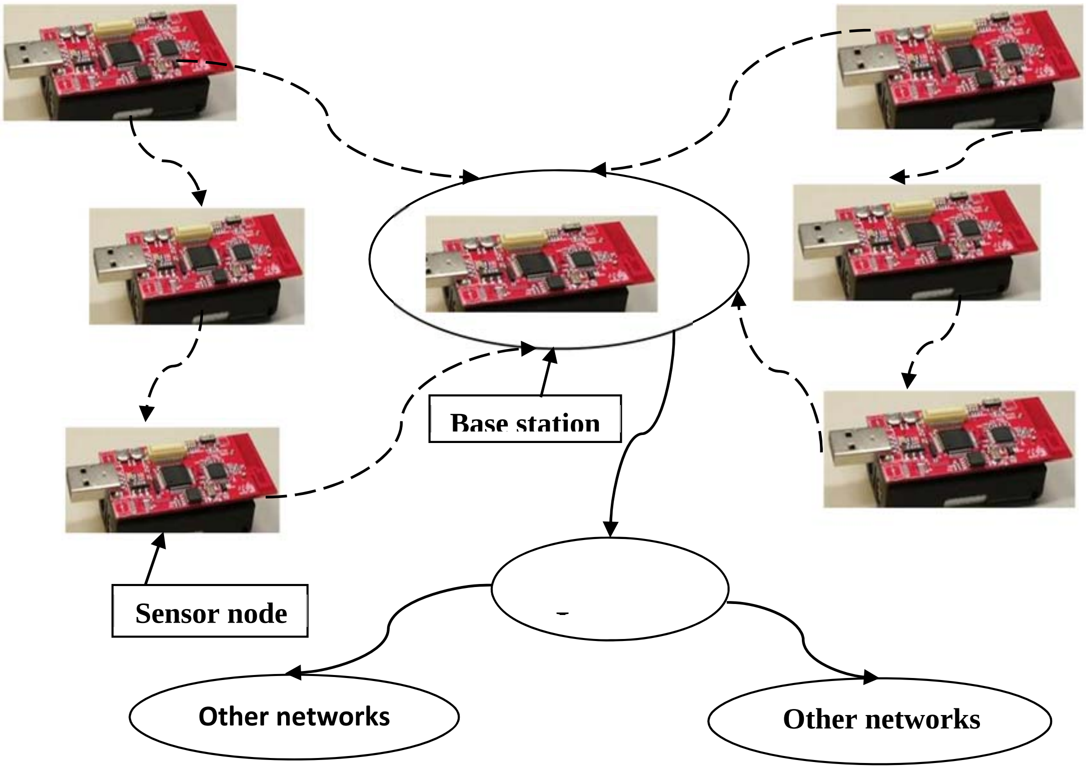

Fig. 1. Components of wireless sensor network

A wireless sensor node consists of four basic components, these components are:

a) The sensing component that senses the physical quantity and collects the required information from the surrounding environment.

b) The communication part, which is responsible for data communication between sensor nodes and base station in a wireless manner.

c) The processor that is used to process the data gathered before transmission to another node or after reception from other nodes.

d) The power system that provides the dc power to other components.

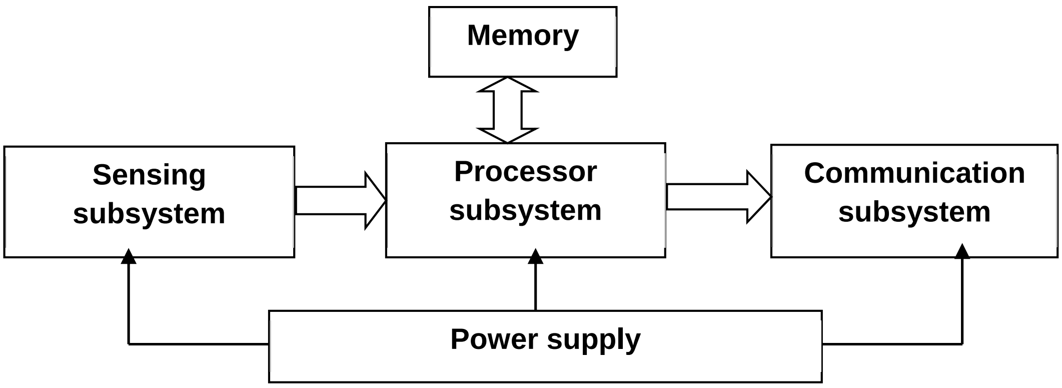

Fig. 2. Wireless sensor node architecture

Designers of WSNs face many challenges and constraints in designing protocols and algorithms for WSN. These challenges are [2]:

1) Energy: It is the most important challenge in WSN design. Sensor nodes have limited and non-rechargeable energy resources. Many WSN applications have sensor nodes deployed in remote and inaccessible areas, batteries of nodes in such applications cannot be recharged, and nodes die as soon as the battery depleted. Energy of wireless sensor node has to be managed carefully in order to extend the lifetime of the wireless sensor network.

Energy consumption is a main factor in WSNs during communication between nodes and it should be saved, so that the sensor battery does not be drained quickly.

There are some procedures that wireless sensor networks designers should take into account to reduce the energy consumption such as [3]:

a) Using energy efficient routing protocols that reduce the energy consumption. The routing protocols should reduce the transmission range as possible since the energy consumption due to transmission is proportional to the square of the transmission distance.

b) Data gathering should be managed and optimized using energy efficient techniques.

c) Avoid transmitting redundant data.

d) Each node should transmit according to a schedule that puts the node into a sleep mode when there is no need for the node operation. In other word, the node should have different operation states based on a schedule (i. e. transmitting state, receiving state, and sleep state).

Thus Energy is the most important issue in WSNs and radio transmission power should be managed and kept at minimum in order to conserve energy and extend the lifetime of the network.

2) Self-Management: As in most applications of WSNs, sensor nodes are employed in a remote areas and hard environments, so they must manage themselves.

Sensor nodes must configure themselves, repair their failures, adapt themselves with environmental changes and cooperate with each others.

3) Wireless Networking: Designing the communication protocols for a WSN faces a number of challenges such as: attenuation and multi-hop communication.

4) Scalability: It is the warranty that the performance of the network does not significantly degrade as the network size (or node density) increases [4].

5) Decentralized Management: The decentralized (distributed) algorithm is more energy efficient than the centralized one.

6) Design Constraints: The main objective of wireless sensor design is to obtain smaller, cheaper, and more efficient devices.

7) Security: It is important because of the following reasons:

a) The information collected by WSNs is sensitive.

b) The sensor nodes are employed in remote and unattended areas which increase their exposition to malicious intrusions and harmful attacks.

c) The wireless communications between sensor nodes make it easy to spy on the transmitted data.

8) Other challenges: there are other challenges that may affect the design of WSNs and sensor nodes such as :

a) Sensors employed on a moving object.

b) Heterogeneity of sensors in WSN that is the network consists of nodes with varying hardware capabilities.

c) Performance and quality requirements that may be needed for specific applications.

In the current era of technology, wireless sensor networks have found their way in many various fields, and several modern and important applications of them are developed. WSNs are more deployed for real life applications than before. Applications of WSNs are such as:

1) Agriculture applications: Wireless sensors are used for temperature and humidity measurements and control, yield mapping and monitoring, fertilizer rate monitoring and control, and water control.

2) Medical care applications: It is one of the most common areas of interest in WSNs researches. Researchers have developed the wireless body area networks (WBAN) that is used mainly for remote monitoring of patients and elders, more details about this application are introduced in [5, 6].

A large number of hospitals and medical centers all over the world are exploring applications of WSN technology to a range of medical applications, such as pre-hospital and in-hospital emergency care, disaster response, and stroke patient rehabilitation [7].

3) Automobile traffic control: Sensors are placed in cars and roads to reduce the congestion and the road accidents [8].

4) Natural phenomena: Wireless sensors are used to detect and control some natural phenomena such as active Volcano monitoring.

5) Pipeline Monitoring: Sensors are used for monitoring and controlling of gas, water, and oil pipelines.

6) Underground Mining: Wireless sensors are used in tunnels monitoring, and accidents avoidance.

7) Military applications: Various Sensor nodes are used to get information about the enemy.

8) Environmental applications: Wireless sensor devices are used in some environmental applications such as pollution monitoring and control.

9) Home automation: Wireless sensors are used for measuring, monitoring, and controlling a lot of home elements, and physical parameters such as the following [7]:

a) Sensor nodes can provide a flexible management of lighting, heating, and cooling systems in home.

b) Sensor nodes provide security for home by always monitoring it and facilitate the reception of automatic notifications upon the detection of unusual events.

c) Sensor nodes can provide the utility of capturing the detailed usage data of electricity, water, and gas.

d) Sensors in homes can enable persons to configure and run multiple systems from a single remote control.

Problem definition

Sensor nodes have limited and non-rechargeable energy resources, as they are deployed in remote and inaccessible areas and thus sensor batteries cannot be recharged or replaced.

Energy is an important issue in WSNs and the energy consumption should be reduced as possible in order to prolong the network life time. The main source of energy dissipation of a wireless sensor is the radio transmission. The communication between sensors and the base station represents most of the dissipated power [9]. Thus radio transmission power should be managed and kept at minimum in order to conserve energy and to extend the lifetime of the network.

Communication protocols for WSNs

The network layer is the most important part in the communication protocol of a wireless sensor network, as it is responsible for finding routes from a sensor node to another and from a sensor node to the base station. Also it estimates route characteristics including route length (in terms of number of hops) and required transmission power .

It is well known that the energy consumed to transmit one bit of data can be used by a sensor processor to perform a large number of arithmetic operations (the power consumed for transmitting one bit of data from transmitter to a receiver that is 100 m away from transmitter is equal to that needed by a sensor processor to execute 3,000 instructions [10]).

Thus the transmission cost represents the most important parameter in energy conservation. In order to conserve energy, the radio transmission power should be kept at minimum.

Routing protocols for WSNs can be classified in different ways based on the protocol operation, the route discovery and the network organization or structure [2]. Fig. 3 shows different classifications of routing protocols developed for wireless sensor networks.

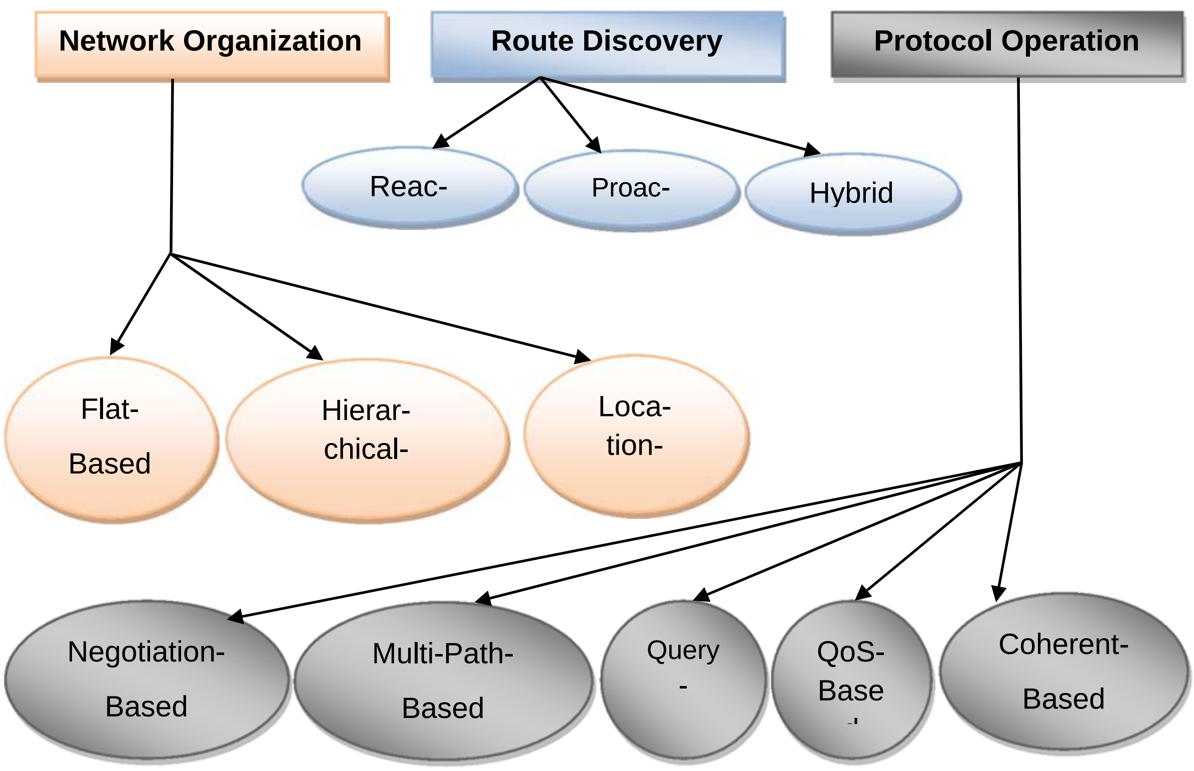

Fig. 3. Classifications of routing protocols for WSNs

Routing protocols for WSNs can be classified into three main categories based on the network organization or structure [11]. These categories are:

1) Flat-based routing protocols: all nodes are assigned equal functions or positions.

2) Hierarchical-based routing protocols: nodes may have different roles in routing operation which is against the flat-based routing protocols. Some nodes will control others and perform more tasks. Nodes don't send their data directly to the base station instead, they send to some of them that have the ability to send to BS.

3) Location-based routing protocols: the routing protocol is built based on the location of each node and data forwarding depends on the sensor location.

Challenges of designing a communication protocol for WSN

The limitations of wireless sensor network resources such as energy, bandwidth, central processing unit (CPU) and storage make the designing of a communication protocol difficult. The main design challenges are discussed in [10] as:

1. Limited energy capacity:

Sensor nodes have a limited energy capacity, as it is battery operated and since the batteries are depleted and they cannot be recharged, thus their nodes die .

Energy is a critical parameter in the network design. If the energy reaches certain threshold level, sensor node doesn't work properly. Thus, routing protocol should be energy efficient to prolong the life time of the sensor network.

2. Scalability:

The routing protocols should be adapted to the network size. The communication links should be convenient with the sensor nodes capabilities (i. e. energy, sensing, processing and radio communication capabilities).

3. Data Aggregation:

Data aggregation technique is used to reduce energy consumption, as similar packets from multiple nodes can be aggregated to ignore redundant data. Thus the number of transmitted packets to the base station is reduced.

4. Wireless sensor network topology:

The communication protocol should be suitable for the network topology which may be a varied topology.

5. Wireless node deployment:

Nodes may be deployed manually or randomly. The random deployment is common but the manual is rarely used depending on the network application.

Random deployment is a big difficulty to the network designer. The nodes may be deployed with high density in some regions and low density in others. Routing protocols should take into account this difficulty.

6. Sensor locations:

Most of routing protocols assume that sensor nodes are embedded with a GPS or other hardware to determine their location.

Clustering of WSN

Clustering is one of the most popular and effective ways that have been used to reduce energy in WSNs [9]. Instead of direct transmission, clustering uses local data aggregation to save the energy. In recent years, wireless sensor networks researchers have done a lot of studies and found that clustering is one of the most effective schemes in increasing the scalability and life time of wireless sensor networks [12].

Clustering of WSNs is the way in which sensor nodes are organized into groups or clusters according to specific properties of nodes and network requirements. The leader of each group of nodes or cluster is known as the cluster head (CH) and the other non CH nodes are known as member nodes [13]. Each CH acts as the local coordinator of transmissions within its cluster (i. e. intra-cluster communication) and also communicates with other cluster heads or with the base station (i. e. inter-cluster communication). Thus cluster head collects and aggregates data from its cluster member nodes and sends it to the base station. Figure 4 shows examples of clustering hierarchy of WSN.

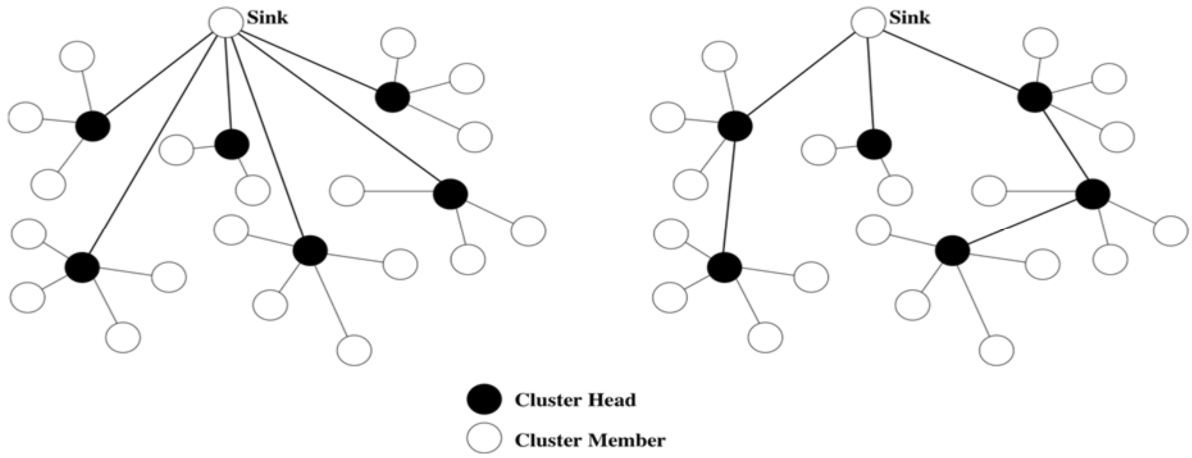

Fig. 4. Clustering hierarchy of WSN [2]

In clustering algorithms, the key factor affecting the network lifetime is the imbalanced energy consumption. In order to balance the energy consumption among nodes in wireless sensor networks with uniform node distribution, clustering algorithms construct uniformly distributed clusters, which have approximately the same number of member nodes and coverage areas [14].

The energy consumed by a CH node is much greater than that of other non-cluster head nodes, as the CH performs more tasks that consume much energy.

The communication between CHs and base station can take one of the following two ways:

1) Single-hop communication,
2) Multi-hop communication.

In single-hop communication, CH nodes send their aggregated data directly to the base station without any mediator. Here the energy consumed by the cluster heads results from data received from member nodes, data aggregation, and data transmission to the base station.

In multi-hop communication, CH nodes exchange data between themselves until reaching the base station. Here the energy consumed by the cluster heads is the energy consumed due to data received from member nodes, data aggregation, and forwarding data to their neighbor cluster heads.

Dynamic clustering is an efficient way for load balancing and distributing the energy consumption among nodes. It dynamically changes the cluster head nodes and thus cluster head position rotates among nodes according to certain parameter (i. e. node residual energy, distance from the base station).

Clustering of WSNs has the following advantageous:

1) It minimizes the routing table stored in each sensor node.

2) It avoids exchanging redundant messages between sensor nodes, and thus saves the communication bandwidth and energy consumption.

3) It reduces the total energy consumption of the network. Sensor nodes can switch to the low-power sleep mode most of the time since clustering schedules activities in each cluster [15].

There are two types of Clustering based on the network type. Clustering of homogeneous WSNs and clustering of heterogeneous WSNs. In homogeneous networks, all nodes have the same initial energy while in heterogeneous networks; the nodes have different initial energy (i. e. some nodes are equipped with more energy than the rest of the nodes in the network [16]).

Clustering Parameters

Clustering protocols are built based on some parameters that change from one protocol to another. These parameters are well known as the clustering parameters that affect the network performance under a certain clustering protocol. Clustering parameters can be summarized as following [17]:

1) Number of clusters (cluster count): In most clustering protocols, the number of cluster heads is predetermined according to a specific criterion and thus the number of clusters is pre-established. This number affects the clustering efficiency and must be chosen to achieve best performance.

2) Intra-cluster communication: It is the communication between nodes and the cluster head inside a cluster. Sensor nodes can communicate with their cluster head either, directly using single hop communication or indirectly through neighboring nodes using multi-hop communication.

3) Member nodes and CH mobility: The member nodes and the cluster heads may be stationary or mobile. Most protocols assume mobile nodes and CHs as this is the case in most of wireless sensor networks. For these mobile nodes, dynamic clustering is used .

4) Cluster-head selection: Sensor nodes are selected to be a cluster head based on its residual energy, its distance from the base station or other announced criteri.

5) Level of hierarchy: Recently, multi-level hierarchal clustering is introduced and achieves better performance.

Thus clustering provides resource utilization and reduces energy consumption in WSNs by minimizing number of sensor nodes that take part in long distance transmission. A lot of clustering algorithms have been designed for wireless sensor networks, where energy awareness is an essential design issue [18].

Cluster based routing protocols

In clustering algorithms, the communication between cluster heads and base station can be either single-hop communication or multi-hop communication. In single-hop communication, the cluster heads send their data directly to the base station. In multi-hop communication, the cluster heads transfer data between each other until reach the base station.

Thus clustering of wireless sensor networks or cluster based routing protocols can be classified into single level cluster based routing protocol and multi-level cluster based routing protocol. We will concern with the multi-level cluster based routing protocols, because of its importance and high performance for densely WSNs.

Multi-level cluster based routing protocols

Multi-level cluster based routing protocols use the multi-hop communication between cluster heads and base station. In these routing protocols there are two types of energy consumption, the intra-cluster energy consumption and the inter-cluster energy consumption.

The intra-cluster energy consumption is the energy consumed due to communication inside the cluster, which is equal to the summation of energy consumed by each member node to send its data to its cluster head. The inter-cluster energy consumption is the energy consumed to forward data from a cluster head to its neighbors [14].

Researches in multi-level cluster based routing are rare compared to those of single-level. Recently, multi-level cluster based routing protocols become more interesting and researchers have proved that they conserve more energy and gives higher efficiency than the single level cluster based routing protocols .

This section reviews some of the most popular and efficient multi-level cluster based routing protocols.

A. Two-Levels Hierarchy for Low-Energy Adaptive Clustering Hierarchy (TL-LEACH)

It is a modified LEACH protocol that applies the clustering in two levels, to conserve more energy in WSNs [19]. Introducing a new level of hierarchy, reduces the transmission distance and allows transmitting of information from sensor nodes to the base station over two different levels which allows better use of network energy. The main difference between TL-LEACH protocol and LEACH protocol is in the set-up phase, where the clusters are created and a node can be primary cluster-head, secondary cluster-head or simple node (SN). In two-level hierarchy: the first level consists of the top cluster-heads or the primary cluster-heads (CHi) and the second level consists of the secondary cluster-heads (CHij) and the simple nodes, indicated as (SN).

TL-LEACH is composed of four fundamental phases: 1) Advertisement Phase; 2) Cluster Setup Phase; 3) Schedule Creation; 4) Data Transmission.

In the first phase, each node decides if it wants to be a primary cluster-head (at top level, CHi), a secondary cluster-head (called CHij) or a simple node (SN), in the current round, where the term round is the same as in LEACH. The primary cluster-head and the secondary cluster-head nodes have to advertise other nodes. The mechanism used in this phase is the Carrier Sense Multiple Access (CSMA).

In the second phase, each secondary cluster head decides to which primary cluster-head it belongs and sends a message to advertise its primary cluster-head. Also each simple node does the same to join a secondary cluster-head.

In the third phase, each primary cluster-head (CHi) creates a TDMA schedule assigning each node a slot to transmit. It also chooses a CDMA code and informs all nodes at second level in its group to transmit using this code.

In the last phase, the nodes send the sensed data to the secondary cluster heads that receive it, aggregate it and send it to the primary cluster heads. The primary cluster heads receive, aggregate and send the data to the base station .

The TL-LEACH protocol achieves better performance than LEACH protocol as it decreases the total energy consumption and increases the life time of the network. This can be an acceptable result since while in LEACH there is only one level before sending to the base station, in the TL-LEACH the use of two levels decreases the distances of transmission and therefore reduces the energy consumptions. TL-LEACH gives a 30 % increase of the lifetime of the network, in comparison to the LEACH [19].

B. Multilevel clustering protocol for wireless sensor networks (MLC)

It is a multilevel clustering protocol that uses different numbers of levels in the hierarchical clustering architecture to reduce the energy consumption in wireless sensor networks [20]. This protocol is different from the well known LEACH protocol. In MLC, cluster heads form a tree starting from the base station which represents the root of the tree. The base station alone represents level – 0 cluster head which is the highest level in the network .

The operation of MLC is divided into rounds. Each round has four phases: discovery phase, cluster head selection phase, cluster head member admittance phase and transmission phase. The first three phases are repeated every round and then followed by a T number of transmission operations. Fig. 5 shows the structure of different levels of MLC.

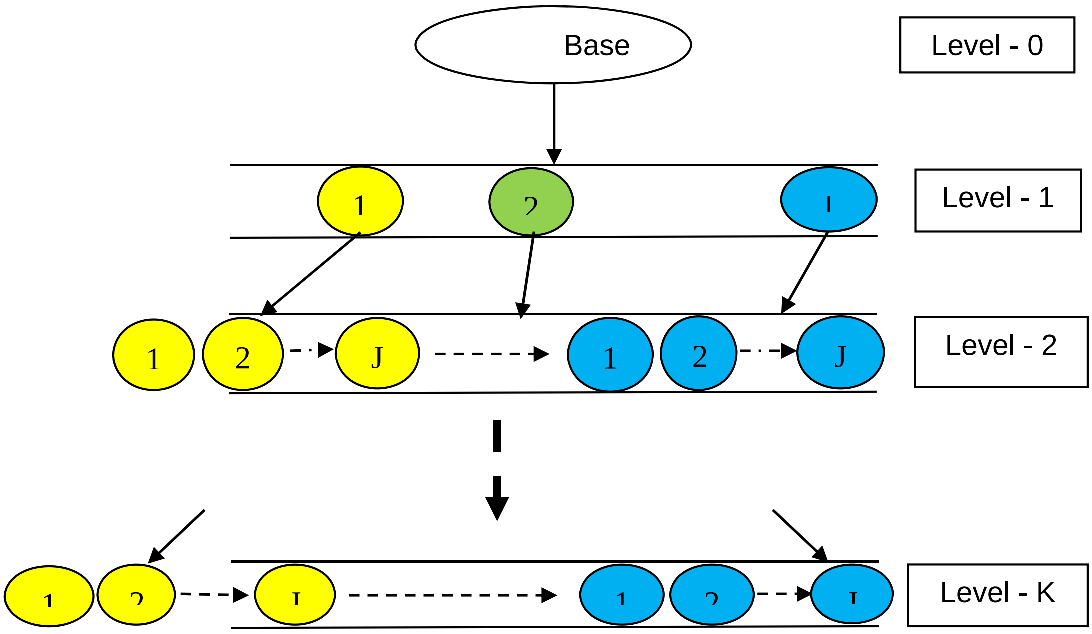

Fig. 5. Structure of MLC with K-levels

1) Discovery phase:

In this phase, each node discovers its neighbors. Each sensor node broadcasts a HELLO message with its maximum transmission range. A sensor node transmits at its maximum power to deliver its message to all nodes in its coverage area which is modeled by a perfect circle.

Each node receives the HELLO messages from other nodes and fills its neighbor-table fields based on the received messages. The neighbor-table is shown in table.

Table.

The neighbor-table

NODE ID	ENERGY	DISTANCE	CLUSTER ID

Where NODE ID is the unique identity of a node; ENERGY is the current residual energy of a node and CLUSTER ID is the unique identity of a cluster that is equal to the NODE ID of the cluster-head of a cluster and DISTANCE is the distance between transmitting and receiving nodes and can be calculated by measuring the received signal strength.

When a HELLO message with a new NODE ID is received, the node had to reply for that message by sending a similar one to the transmitter. Node should reply to create a bidirectional link between the two nodes .

At the end of each round, every node including the sink clears its neighbor-table and begins to create a new neighbor discovery process.

2) Cluster head selection phase:

In this phase, the cluster heads of different levels are selected where a cluster-head can select cluster-heads at the next level. At level-0 (represented by base station), the sink selects I number of nodes from its neighbor-table as the next level cluster heads and broadcasts a NOTIFY message to inform them. The sink selects I cluster heads using minimum cost model which chooses the cluster heads based on the distance from the base station and the residual energy as explained in [21]. Similarly, other cluster heads of higher levels are selected .

3) Cluster head member admittance phase :

After the cluster head selection phase has been completed, each cluster head begins to build its cluster. Each cluster head broadcasts an advertisement message (ADERT message). The neighbor nodes receives the message and replies with a join message (JOIN message) to the nearest cluster head, that it has received his message with the strongest signal strength. Cluster heads accept the join message by replying with an acceptance message .

4) Transmission phase:

In this phase, each node transmits its sensed data to its cluster head using an allocated TDMA slot. The different time slots are allocated to the member nodes by their cluster heads. Cluster heads receive the sensed data from their member nodes and aggregate it. Each cluster head sends the data upstream to another cluster head until the data reach the base station .

Simulation results show that at certain values of the network parameters the MLC protocol achieves a 300 % performance improvement over the LEACH protocol [20]. Thus MLC increases the life time of the network. Also it achieves higher reliability in delivering the sensed data to the base station and gives better network coverage area.

C. Dynamic Multi Level Hierarchical Clustering Approach For Sensor Networks (DMH)

It is a multilevel dynamic clustering protocol in which clusters are re-organized according to traffic patterns in the active network [22]. The cluster size, the number of nodes in a cluster and the level of hierarchy varies based on the system state .

This approach uses non equal size clusters and the size of the cluster changes based on its position from the base station. Also DMH allows multi hop routing inside the cluster which is similar to what happens in PEGASIS. The operation of DMH is divided into three phases :

1) Cluster formation ;
2) Data aggregation within cluster ;
3) Routing of aggregated data to base station.

The first phase is the cluster formation phase, in which clusters are formed according to self adaptive algorithm and this process is repeated periodically after a constant time *Tc* (this is what is called in other protocols as round).

At the initial stage of the cluster formation algorithm, all the nodes send its information to its neighbors. Thus all nodes know the status of its neighbors and nodes with highest degree and greatest residual energy are selected to be a cluster heads. Cluster heads send confirmation signal and all other nodes with closer vicinity (in terms of greater received power) replies to this signal and join a cluster .

In this phase, the information is exchanged between various nodes, cluster heads and base station using two way handshaking model. Also RTS-CTS is used as the MAC layer type. The sizes of the clusters are set initially in this phase and depend on the distance from the base station. The more distance from the base station, the larger size the cluster head. The small size clusters will have small energy as the number of nodes is small and this energy is mainly used in routing data rather than communication inside the cluster.

The second phase is the data aggregation phase or the steady state phase in which the multilevel hierarchical clustering is created. The multi-level hierarchy is created from high level traffic areas and low level traffic areas. The cluster heads in the low traffic areas are the higher level cluster heads and the cluster heads of high traffic areas are the lower level cluster heads. The low level cluster heads aggregate their data and send it to the higher level of cluster heads.

The traffic is measured by the number of messages exchanged by neighboring nodes. The traffic level of cluster head are indicated by a constant number *T¬K*; as the number increases the more traffic in the corresponding area exist .

The communication inside the cluster can be done using single hop or multi-hop communication depending on the distance between nodes and their cluster head. For multi-hop communication, the data are transferred in a chain like what in [23].

In the last phase, the aggregated data of the highest level of hierarchy are routed to the base station. Simulation results show that DMH protocol achieve better performance than LEACH, but this for network with small number of nodes only. For large number of nodes the protocol becomes not robustness.

D. A cluster-based routing protocol for wireless sensor networks with non uniform node distribution

It is a cluster based routing protocol that is used for wireless sensor networks with non uniform node distribution [24]. This protocol builds clusters based on energy aware distributed clustering algorithm (EADC), which uses a competition range to construct clusters of equal sizes. Cluster heads choose nodes with high energy to be their next hops when they send their aggregated data to the base station.

This protocol consists of energy aware distributed clustering algorithm, which is used to build clusters and cluster-based routing algorithm, which is used to route data outside clusters (i. e. inter-cluster communication). The routing algorithm used here is an inter-cluster energy efficient multi-hop routing protocol, in which cluster heads don't send data directly to the base station; instead they choose their next hop from their neighbors. The neighbor cluster head with higher residual energy and a smaller number of cluster members is selected as the next hop. Thus the energy consumption among cluster heads can be balanced.

In order to simplify the network model, the authors of this protocol assume the following assumptions [14]:

1) All sensor nodes and the BS are stationary after deployment.
2) There are N sensor nodes that are distributed in a square field.
3) The BS is fixed and located out of the sensor field .
4) All sensor nodes can be heterogeneous, but their energy cannot be recharged.
5) All sensor nodes are location-unaware.
6) All nodes can use power control to vary the amount of transmitted power.
7) Base station has a sufficient energy resource and the location of the BS is known by each node.
8) Each node has a unique identity (id).

Conclusion

In this work, design aspects concerned with the development of WSNs are discussed. Energy is the main design problem, thus a robust energy efficient communication protocol is a perfect solution. In our work, different types of cluster based routing protocols are reviewed.

For multi-level cluster based routing protocols, we discuss how the existing protocols apply higher levels of clustering and how the cluster heads of higher levels are chosen. Also the advantageous and disadvantageous of each protocol is introduced.

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