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A survey on energy efficient coverage protocols in wireless sensor networks

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Energy efficiency

Abstract A Wireless Sensor Network (WSN) is used to monitor an area for events. Each node in the WSN has a sensing range and a communication range. The sensing coverage of a sensor node is the area determined by the sensing range of the sensor node. Sensing coverage of the network is the collective coverage of the sensor nodes in a WSN. Sufficient number of sensor nodes need to be deployed to ensure adequate coverage of a region. Further, since sensor nodes have limited battery life, it is also essential to reduce the energy consumption. This would help improve the network lifetime and thus the coverage lifetime. To reduce energy consumption in the WSN, some of the nodes with overlapping sensing areas could be turned off using a coverage optimization protocol. In this paper, we discuss various coverage optimization protocols. These protocols are broadly classified as *clustering* and *distributed* protocols. Further, these protocols are classified based on the type of sensing model used, node location information, and mechanism used to determine neighboring node information (based on probe or computational geometry). In this paper, we review the key coverage optimization protocols and present open research issues related to energy efficient coverage.

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1. Introduction

Wireless Sensor Networks (WSNs) have been widely considered as one of the most important technologies for the twenty-first century (Zheng and Jamalipour, 2009; Chong and Srikanta, 2003). A typical Wireless Sensor Network (WSN) (Zheng and Jamalipour, 2009; Chuan et al., 2012; Raghavendra et al., 2011; Akkaya and Younis, 2005) consists of a large number low cost, multi-functional sensor nodes typically operate on limited battery power and are deployed to monitor an area of interest. These sensor nodes are typically small in size with inbuilt micro-controllers and radio transceivers. Thus, sensor nodes have the ability to sense external events, process the sensed data and transmit it. WSNs are widely used for environmental condition monitoring, security surveillance of battle-fields, wildlife habitat monitoring, etc. (Mulligan and Ammari, 2010). A WSN has the following characteristics:

- Dense Node Deployment: Sensor nodes are usually densely deployed in an area to be monitored. The number of sensor nodes in a sensor network is usually higher than that of a MANET (Chlamtac et al., 2003; Hoebeke et al., 2004).
- Limited Energy Resources: Sensor nodes are usually powered with small batteries. In certain applications, they are deployed in a harsh or hostile environment, where it would be very difficult or even impossible to replace or recharge the node batteries.

- Self and Auto-Configuration of Nodes: Sensor nodes could be randomly deployed without careful planning. Once deployed, sensor nodes could autonomously configure the network.
- Application Specific Nodes: Sensor networks are usually application specific. Sensor nodes are designed and deployed for a specific application. Thus, the design requirements of a sensor network could change based on the application requirement.
- Frequent Topology Change: In a sensor network, the topology could change frequently due to node failure, energy depletion or channel fading.
- Coverage Area and Data Redundancy: In most sensor network applications, sensor nodes are densely deployed in a region of interest. Therefore, there might be a possibility that more than one sensor node is monitoring a sensing area. Thus, the data sensed by multiple sensor nodes may have a certain amount of correlation or redundancy.

In a WSN, each sensor node has a *sensing area coverage* (Mulligan and Ammari, 2010; Akyildiz et al., 2002; Amit and Sajal, 2008) based on its sensing range (R_s). The *sensing area coverage* (or sensing coverage) is the region that a node can observe or monitor within its sensing range as shown in Fig. 1. The *network coverage* (Mulligan and Ammari, 2010; Akyildiz et al., 2002; Amit and Sajal, 2008) could be interpreted as the collective coverage by all the ACTIVE sensor nodes in the WSN. Further, each sensor node has a *radio area coverage* (or radio coverage) (Mulligan and Ammari, 2010; Akyildiz et al., 2002; Amit and Sajal, 2008) based on its communication range (R_c). The *radio coverage* (see Fig. 1) bounded by R_c, is the region or area within which an ACTIVE sensor node can communicate with at least one other sensor node. *Sensing coverage* ensures proper event monitoring while *radio coverage* (Mulligan and Ammari, 2010; Akyildiz et al., 2002; Amit and Sajal, 2008) ensures proper data transmission within the WSN shown in Fig. 1. The sensor nodes in a WSN may be deployed such that multiple nodes may monitor an area. *Coverage degree* (C_d) refers to the number of sensor nodes actively monitoring an area. $C_d = n$ means n sensors are actively monitoring an area. However, a *sensing void or hole* occurs when no sensor actively monitors an area. To maximize the network lifetime it is essential to minimize the number of ACTIVE nodes while still achieving maximum possible sensing and radio coverage.

The sensing coverage and radio coverage could be *full* or *limited* depending on the needs of the application (Winston and Paramasivan, 2011). (1) *Full sensing and radio coverage*: This is required for applications wherein every location in the field is required to be monitored by at least one sensor node. It is widely used in intrusion detection, field monitoring, etc. (2) *Limited sensing and radio coverage*: Some of the applications require limited coverage. For example, temperature monitoring in a region. Compared to full coverage, limited coverage requires lesser number of sensor nodes. (3) *Instant sensing and radio coverage*: some applications require the coverage to be such that sensing of an event is done at the instant of time when the event occurs. Therefore, required sensors need to be active at the required point in time only. Rest of the time, the sensors can go to sleep. Instant coverage is with respect to time, therefore, instant coverage could be full or limited, depending on the application. Thus, based on requirements of sensing coverage type and network coverage lifetime, an appropriate duty cycle for the sensor nodes needs to be determined.

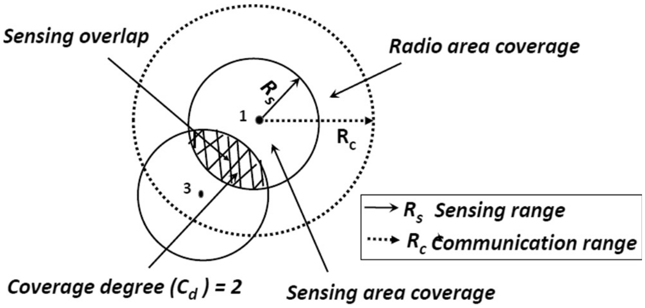


Figure 1 Sensing and communication range of node.

Sensor network lifetime could be defined as the time duration for which a network is able to perform sensing activity and able to transmit data toward the base station or sink node. During this time period, some of the nodes might become unavailable due to hardware failure or energy depletion. At the same time there might be the possibility of deploying additional nodes in order to maintain adequate *coverage degree* (C_d). In sensor network, if multiple sensor nodes are monitoring the same sensing area, then, there could be a possibility of unnecessary coverage redundancy which would result in wastage of energy. A wireless sensor node has limited battery resources. Therefore, it is important to identify redundant ACTIVE nodes and switch them off. Appropriate duty cycle for the nodes will help reduce or eliminate coverage redundancy and result in efficient usage of battery (Basagni et al., 2013, Knight et al., 2008). There are many techniques which can ameliorate such coverage redundancy. In addition, protocols need to detect when coverage of an area has stopped and a sensing void has occurred. Most coverage protocols, aim to ensure energy efficient coverage by determining appropriate duty cycle of nodes (More and Raisinghani, 2015). Some coverage protocols propose movement of nodes or deployment of additional nodes to handle sensing voids (Le and Min Jang, 2015). The node duty cycle could be frequent, periodic and/or based on some coverage metrics, identifying redundant nodes which can be put into sleep state. If the sleep period determined for redundant nodes is not accurate, there is a possibility of frequent and unnecessary wake-ups of sleeping nodes which could lead to energy wastage. However, the optimal duty cycle or wake-up rate is dependent on a number of factors and the solution would depend on the application's requirements. In order to determine optimized wake-up rate of sleeping nodes, we must consider (a) Which factors (battery, coverage node degree, terrain, etc.) should each node consider to determine its duty cycle? (b) When should each node make such a decision? (i.e. when and how many times should this mechanism be triggered) and (3) How long should the sensor node remain in the SLEEP or ACTIVE state? In this paper, we focus on energy efficient coverage protocols which maintain adequate coverage and ensure a longer network lifetime.

The rest of the paper is organized as follows. In Section 2 we have defined some preliminaries related to sensor networks. In Section 3, we discuss various sensing coverage optimization protocols. Based on our analysis, we present open research issues, in Section 4. We present our concluding remarks in Section 5.

2. Preliminaries

In this section, we describe the sensing models which are widely used in WSN. In WSN, different sensing models can be used based on application requirements (Zhu et al., 2012; Hossain et al., 2012; Sushil and Lobiyal, 2013; Bhowmik and Giri, 2013). The *sensitivity or sensing ability* S of a sensor node diminishes as the distance from a point of interest increases. A sensing model represents the sensitivity of a node. In a WSN, the sensing models can be categorized as *deterministic* or *probabilistic*. For example, we assume that sensor node i is monitoring a point p where an event is detected or observed.

2.1. Sensing models

In WSNs, each sensor node has a certain amount of sensing ability to detect an external event in the physical environment. A node's sensing ability is limited due to sensing range and its accuracy. Thus, a node can only cover/sense a limited physical area of an environment. Therefore, sensing models have an impact on area coverage, coverage lifetime and coverage redundancy in a WSN. The sensing models broadly classified as *deterministic* or *probabilistic*.

2.1.1. Deterministic sensing model

The deterministic sensing model is also known as a *binary sensing model* where a node is capable of sensing events only at points that lie within its sensing range and cannot sense at any point outside the sensing range. The sensing range of each node is assumed to be a uniform circle of sensing radius R_s. An event that occurs at point p within the sensing range of the node (i) is assumed to be detected with probability (S) *1* while any event outside the range is assumed to be detected with probability *0* (i.e. cannot be detected). Thus,

$$S = \begin{cases} 1 & \text{if } R_s \geqslant d(i,p) \\ 0 & \text{otherwise} \end{cases}$$

where, $d(i,p)$ is the euclidean distance between i and p.

The deterministic sensing model can also be expressed as a *variable radii circular sensing model* or *tunable sensing model* (Soreanu and Volkovich, 2009; Wang and Medidi, 2007; Cardei et al., 2006). The tunable sensing model is used to set up minimum number of active nodes while satisfying the coverage requirements. Thus, using different sensing radii for different nodes ($R1 \leqslant R2 \leqslant R3$), the sensing area can be better covered, with lesser overlap in the network field. This helps in lowering the energy consumption by ensuring lower density of active nodes.

2.1.2. Probabilistic sensing model

The probabilistic sensing model is more realistic since the *sensing ability* or *sensitivity* of the node decreases as the distance increases.

$$S = \begin{cases} 1 & \text{if } R_s - r \geqslant d(i,p) \\ e^{-\lambda\alpha^{\beta}} & \text{if } R_s - r \leqslant d(i,p) \leqslant R_s + r \\ 0 & \text{if } R_s + r \leqslant d(i,p) \end{cases}$$

where, r is a measure of the uncertainty in the detection radius of the sensor node. $\alpha = d(i,p) - (R_s - r)$, λ and β are detection parameters. This model reflects the behavior of range sensing devices such as infrared and ultrasound sensor nodes. Further, the sensing capability is affected by environmental factors such as noise, interference, obstacles, etc. Hence, to account for these factors various probabilistic models for sensing have been defined. For example, the sensing signal could vary as a function of distance. These functions could be exponential (Zou and Chakrabarty, 2005; Zou and Chakrabarty, 2004), polynomial (Liu and Towsley, 2004) or staircase (Ahmed et al., 2005). The probabilistic sensing models are further classified as (a) Elfes sensing model (b) Shadowing fading sensing model (c) Log-normal shadowing and Rayleigh Fading sensing model. More details on these sensing models are discussed in (Tsai, 2008; Sushil and Lobiyal, 2013). However, in this paper, we have considered protocols which use the deterministic sensing model for energy efficient coverage.

2.2. Centralized/distributed algorithm

Once sensor nodes are deployed in the network field, an algorithm is used to determine whether sufficient coverage exists in the network. The centralized algorithms have a common central entity which performs all network-related operations (data fusion, data gathering, forwarding etc.) and thus has the common shortcomings of a centralized algorithm i.e. the central entity is a single point of failure. In the cluster based algorithms, the mechanism of calculating the percentage of cluster heads in the network is not dependent on the node density due to which uniform and/or full coverage in the network may not be maintained. Also, the transmission from cluster heads farther away from the base station, as well as communication between multiple cluster heads, requires higher power than single hop communication. This increased energy consumption causes nodes to die quickly. Due to this, there is a possibility of *sensing void* in the network. A distributed algorithm on the other hand is run on each node within the network. In this algorithm, each node has the capability to decide its working mode with the help of neighboring active node information. Compared to centralized algorithms, distributed algorithms would tend to have uniform energy consumption which would lead to increased network lifetime and coverage. In this paper, we discuss clustering as well as distributed coverage optimization protocols.

2.3. Sensor node deployment strategy

Sensor node deployment is one of the important design criteria for ensuring energy efficient coverage in a WSN. Appropriate node deployment can handle a range of issues in the WSN, such as, coverage redundancy, coverage degree, data routing, data fusion, connectivity, and communication. In addition, it can extend the lifetime of a sensor network by minimizing energy consumption. The node deployment methods addressed in Poe and Schmitt (2009) has random, square grid and

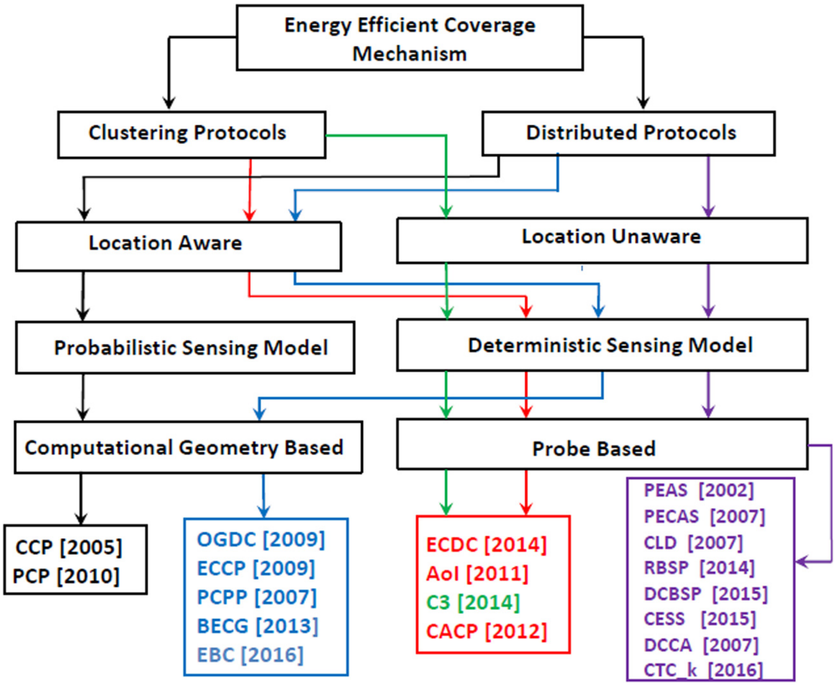


Figure 2 Classification of sensing coverage.

pattern-based *Tri-Hexagon Tiling (THT)* deployment. Parker et al. (2003) have proposed a deployment method for environmental monitoring and urban search and rescue operation using an autonomous helicopter. Further, the deployment method can be determined using the virtual interaction between sensor nodes based on some physical models, such as potential field model and fluid flow model are discussed in Howard et al. (2002) and Pac et al. (2006). Similarly, another approach proposed in Umeki et al. (2009) is *sky mesh* for an ad hoc network system using a flying balloon, for targeted disaster rescue support operation. In this paper, we have discussed deterministic and random node deployment schemes for energy efficient coverage in sensor networks. In the next section, we discuss the details of existing coverage protocols and analyze their working in terms of the number of active nodes, sensing and radio coverage range, energy efficiency and area coverage.

3. Coverage optimization protocols

In this section, we discuss energy efficient coverage protocols used in wireless sensor networks. Various coverage optimization protocols have been described in the literature (Akkaya and Younis, 2005; Akyildiz et al., 2002; Mulligan and Ammari, 2010; Wang and Xiao, 2006). The coverage optimization protocols in this paper are broadly classified as *clustering protocols* and *distributed protocols*, as shown in Fig. 2. Our survey focuses only on protocols which follow the deterministic sensing model. Most of the clustering protocols require location information. The node location is determined using GPS, compass or directional antennas. In the next section, we describe the location unaware distributed coverage protocols.

3.1. Location unaware distributed protocols

In these techniques, the sensor nodes use probes to find active nodes in their neighborhood. Using this information the probing nodes decide their sleep-wakeup cycle. All of these techniques assume static sensor nodes, i.e. the nodes do not move once they are deployed. These techniques consider uniform node characteristics i.e. all nodes have the same, and fixed, sensing coverage range, same radio coverage range and all are location unaware. In the sections below, we first discuss PEAS (Fan Ye et al., 2002), PECAS (Gui and Mohapatra, 2004), CLD (Yen et al., 2007), RBSP (More and Raisinghani, 2014), DCBSP (More and Raisinghani, 2015), and DCCA (Tezcan and Wang, 2007). PEAS is the underlying protocol both in PECAS and CLD.

3.1.1. Probing environment and adaptive sleeping

Each node in PEAS (Fan Ye et al., 2002) has three operating modes: *sleeping, probing* and *active*. The network lifetime increases by keeping only the necessary nodes active and the rest are kept in sleep mode. In PEAS, a sleeping node occasionally enters probing mode and broadcasts messages (probes) within its local probing range and checks whether an active node exists within its probing range. The probing node enters the active state only when it receives no replies from its working neighbors, else it goes back to sleep mode. The probing node calculates a random sleeping time before the next round of probing, based on the reply message received from the active node.

Analysis: The aim of PEAS is to maximize network coverage and connectivity by waking up a minimum number of nodes. PEAS does not maintain neighbor node information, so state overhead is low. PEAS can obtain desired working

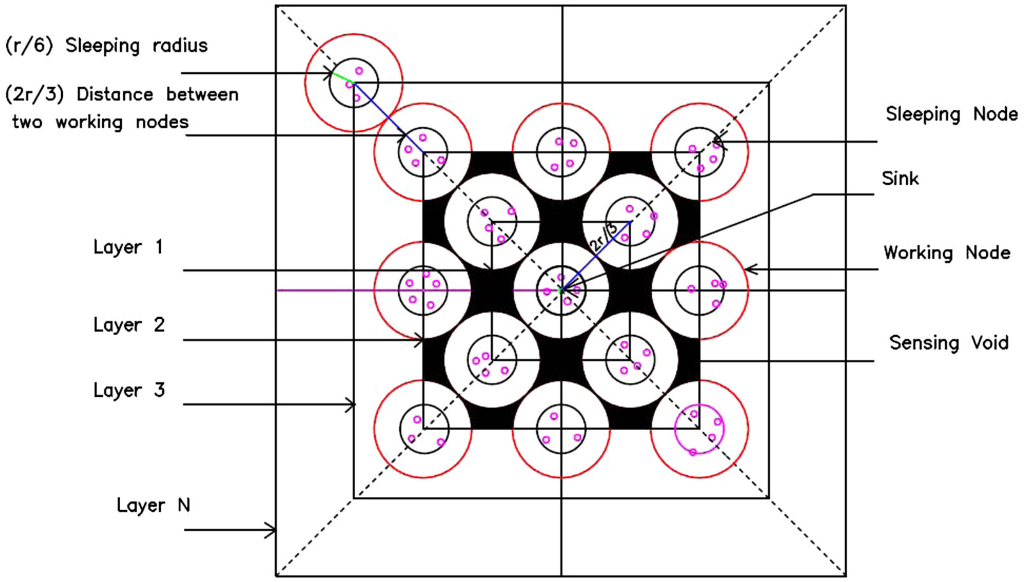


Figure 3 Schematic diagram for CLD; shaded areas are sensing voids.

node density by counting the number of reply messages. The authors show that the network lifetime increases linearly with the number of nodes. PEAS does not provide a guarantee for sensing coverage even in case of *K-coverage* where K indicates coverage degree. A working node once it becomes active, never enters into sleep state again. This may cause unbalanced energy consumption in the network and also a sensing void. In addition, failure of nodes, due to energy depletion, may cause a network partition. However, PEAS is useful for extending the lifetime of a high-density sensor network, in a harsh environment. If the node density is not high enough then some of the probing nodes may not find any working node in their probing range. Thus, probing nodes may enter into the active state, which would lead to a reduction in the network and node lifetime. PEAS can work for variable *coverage degree* (C_d). $C_d = n$ means that n active sensor nodes are monitoring a common sensing area, to ensure guaranteed event detection or guaranteed area coverage within the network. Thus, in PEAS, for $C_d = 3$ the coverage lifetime would be longer than that for $C_d = 4$ or 5. In case of $C_d = 3$, lesser number of working nodes would be required to monitor the network field and thus larger number of nodes can enter into sleeping state. This would reduce the energy consumption and increase the network lifetime, as compared to the case where $C_d = 4$ or 5. PEAS can handle node failures. For the case of 38% node failure (Scenario S_{PEAS} Simulation area: Area (A) = $50 * 50\ \mathrm{m}^2$, $R_s = 10\ \mathrm{m}$,$R_c = 10\ \mathrm{m}$, Number of nodes (N) = 160), the coverage lifetime of PEAS drops only between 12% and 20%. However, this is due to the probing mechanism and the probing rate set for the particular scenario. Next, we discuss PECAS (Gui and Mohapatra, 2004) which overcomes some of the limitations of PEAS.

3.1.2. Probing environment and collaborating adaptive sleeping

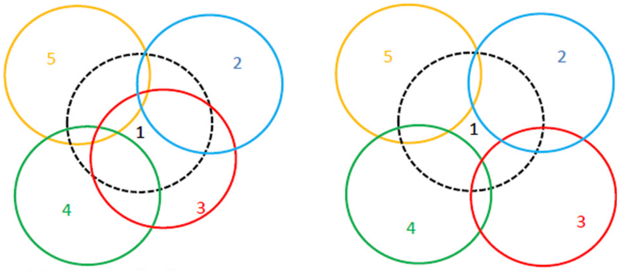
PECAS (Gui and Mohapatra, 2004) is an extension to PEAS. In PECAS, when a node wakes up and probes, if no other nodes are active within its probing range, then that node becomes active. However, in contrast to PEAS, in PECAS, the active node enters into sleep mode after a specified period of time. In addition, the active node also indicates its remaining working time, in its reply messages to the probing nodes. Using this information, when the active node enters sleep state, other sleeping nodes in the neighborhood wakeup and probe again.

Analysis: The main limitations of PEAS, such as network partition and energy unbalance, are overcome in PECAS. This is because PECAS does not allow working nodes to operate continuously until energy depletion. The occurrence of sensing void is reduced in PECAS because a working node schedules itself to enter into sleep mode after some specified time. If the working time duration of active node is set to infinity, then the behavior of PECAS protocol is the same as that of PEAS protocol. PECAS has higher message exchange overhead as compared to PEAS because of the number of probes that need to be sent. In PECAS, the number of working nodes are controlled by *probing range* and *working time duration*. If the working time duration is infinity, the ACTIVE node would remain on till its battery drains, similar to the concept in PEAS. In PECAS (simulation scenario S_{PEAS} as mentioned above), when the probing range (40 m) is kept twice that of the sensing range, the energy saving is 79.2%, 83.4% and 86.2% for *working time duration* of 1.0 s, 10.0 s and infinity working durations, respectively, as compared to PEAS. Thus, as the *working time duration* of the ACTIVE nodes increases, the energy saving increases. This energy saving is due to the increase in the sleeping time duration of other nodes. This significantly reduces the PROBE/REPLY message exchanges which further lowers the energy consumption. In PEAS and PECAS, the nodes are randomly deployed. The sensors need to transfer data using ad hoc routing. This ad hoc routing can cause faster battery depletion of some nodes, depending on their location in the network. In the next section, we discuss Control Layer Deployment Protocol(CLD) (Yen et al., 2007) that uses deterministic node deployment and is based on PEAS.

3.1.3. Controlled layer deployment

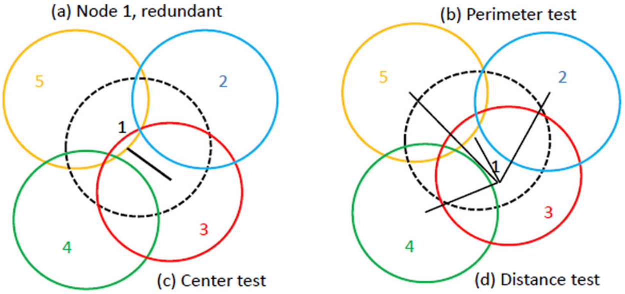
CLD (Yen et al., 2007) proposes deterministic node deployment and uses the PEAS algorithm. The aim of deterministic node deployment in CLD is to reduce the *cascading effect*. The *cascading effect* is with reference to nodes which are used on data transfer paths to the sink. The battery of nodes which are on multiple paths toward the sink drains faster as compared to others. This is known as the cascading effect. In CLD, as shown in Fig. 3, the distance between two working nodes is maintained as 2r/3. Where r is the sensing radius. The sensing radius of each working node is r/3. The nodes are deployed in multiple *layers* to cover the area to be monitored, as shown in Fig. 3. The working nodes are surrounded by sleeping nodes at a distance of r/6. Since the battery of nodes near the sink is expected to drain faster due to a cascading effect, additional sleeping nodes are deployed nearer to the sink. Once the deployment is done, PEAS is used to ensure that a sufficient number of working nodes are active. A sink is placed at the center of the total area to be monitored.

Analysis: CLD is suitable for those applications where the environment is known beforehand and deterministic deployment is possible. CLD maintains full area coverage and energy efficiency by reducing the *cascading effect*. However, the *cascading effect* is not completely removed because nodes are always deployed around the sink using deterministic node deployment to maintain connectivity. In addition, sensing voids are always present in the monitoring region, as shown in Fig. 3. Thus, full coverage is not possible. Authors show that, CLD helps to achieve a longer coverage lifetime as compared to PEAS. The coverage lifetime of CLD is 25% higher as compared to PEAS for node density of 550. This is due to an effectively planned deployment (deterministic deployment) of nodes which results in higher power saving. However, the overall network lifetime is 36.35% more in the case of PEAS due to the lesser number of active nodes required for coverage. In CLD, the deterministic node deployment requires higher number of nodes for full area coverage which leads to higher energy consumption within the network as compared to PEAS.



(a) Node 1, redundant

(b) Perimeter test



(c) Center test

(d) Distance test

Figure 4 Coverage calculation.

3.1.4. Random backoff sleep protocol

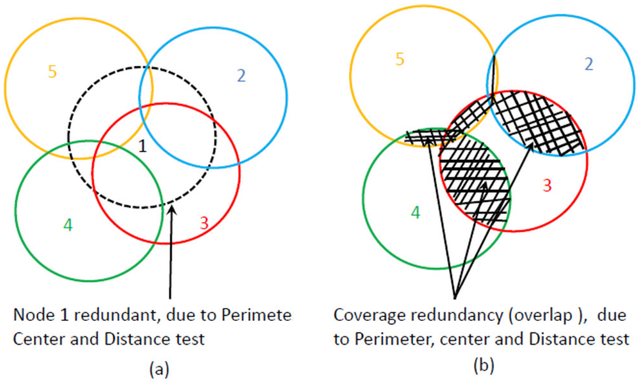
RBSP (More and Raisinghani, 2014) is a probe based protocol which utilizes the information about the residual energy level of the current active node. RBSP protocol employs a novel backoff algorithm for calculation of *Backoff Sleep Time*. The proposed protocol uniformly chooses a *random value* from *Sleeping Window* based on the residual energy of the active node. Using this mechanism, when an active node has high residual energy, the probability of a neighbor node turning *on* is very low. Similarly, when an active node has lower residual energy, the probability of a neighbor node turning *on* is very high.

Analysis: RBSP is a probe based protocol, uses a random *sleeping window*, based on the amount of residual energy at an *active* node. RBSP ensures that the probability of neighbor sleeping nodes becoming active is inversely related to the residual energy level of the current active node. In RBSP, the neighboring sleeping nodes wake-up frequently when the residual energy of the current active node is very low. This unnecessary frequent wake-up of a sleeping node, causes energy wastage and reduces the network lifetime. RBSP maintains sufficient number of nodes active for a longer period of time, therefore, RBSP has 12.5% higher and longer coverage lifetime as compared to PEAS. However, RBSP does not handle *sensing voids* hence, full area coverage is not maintained (More and Raisinghani, 2015). The average energy consumption of RBSP is 19% lesser than that of PEAS due to *Backoff Sleep Time* derived from dynamic sleeping window based on the residual energy level of active nodes.

3.1.5. Discharge curve backoff sleep protocol

DCBSP (More and Raisinghani, 2015) is an energy efficient coverage protocol based on battery discharge curve. DCBSP uses a *normalized generic battery discharge curve* to determine the *Backoff Sleep Time* for neighboring sleeping nodes. Each node in DCBSP has three operating states which are similar to RBSP (More and Raisinghani, 2014): *SLEEP*, *FLOAT* and *ACTIVE*. Initially all nodes are in sleeping state. Upon expiration of backoff sleep timer the sleeping node wakes up and enters into a FLOATING state. The FLOATING node broadcasts a HELLO message within its sensing range R_s. If any ACTIVE node/nodes are present within the sensing range of this FLOATING node then the ACTIVE node responds with a REPLY message which includes a *Backoff Sleep Time (BST)*, (based on normalized generic battery discharge curve mapped to residual energy of the ACTIVE node). The floating node then changes its state to SLEEP mode. If the FLOATING node does not hear any REPLY, then it enters into ACTIVE state and remains ACTIVE until it consumes all of its energy.

Analysis: DCBSP is a probe based, location unaware protocol. The optimal *Backoff Sleep Time* derived from normalized generic discharge curve, avoids random and unnecessary frequent wake-ups of sleeping nodes. Due to this, sleeping nodes wake-up only close to the death of current ACTIVE nodes. This leads to lesser energy consumption and increased network lifetime. DCBSP allows sufficient count of sensor nodes to remain in active state, due to which coverage redundancy is minimized. DCBSP maintains the sufficient count of ACTIVE nodes in order to maintain adequate sensing area coverage. The authors show through simulation that, area coverage of



Node 1 redundant, due to Perimete Center and Distance test

(a)

Coverage redundancy (overlap), due to Perimeter, center and Distance test

(b)

Figure 5 Coverage overlap due to perimeter, center and distance test.

DCBSP is 73.45% while it is 63.14%, 47.17% and 42.62% for PECAS, RBSP and PEAS. The average energy consumption of DCBSP is lesser than that of PEAS by 39% and less by 25% and 15% as compared to RBSP and PECAS respectively. Thus, DCBSP maintains higher, longer area coverage and network lifetime as compared to PECAS, RBSP and PEAS.

3.1.6. Distributed coverage calculation algorithm

Tezcan et al. have presented DCCA (Tezcan and Wang, 2007), which uses the coordinate information to determine redundant sensor nodes. DCCA reduces coverage redundancy and maintains network connectivity by selecting working nodes with the help of *perimeter*, *center* and *distance* tests applied to neighbor nodes. For example, Fig. 4(a) shows the coverage calculation to identify redundant nodes. A node uses the perimeter-test to check whether its entire perimeter is covered by other neighboring nodes. In Fig. 4(b), node 1 perimeter is covered by neighbor nodes (2,3,4,5). However, a part of the area of node 1 is not covered by its neighbor nodes. Thus, the center test determines whether the center of node 1 is covered by at least one of its perimeter neighbor nodes, as shown in Fig. 4 (c) (node 3 covers the center of node 1). Finally, the distance-test, with reference to the neighbor node (i.e. node 3) covering the center of node 1, ensures that there is no uncovered area inside the sensing region of node 1. In the distance-test (Fig. 4(d)), other neighbor nodes must satisfy the condition: $d(3,i) \leqslant d(3,1) + R_s$ where i is 2, 4, 5. After finding the sufficient number of redundant nodes, DCCA executes *energy-aware redundant elimination method*, to construct the optimal-coverage set. Here, energy-aware redundant elimination method uses the *coverage benefits function* which is based on the area covered by the overlapping nodes and their residual energy. The coverage benefits function determines the *optimal-coverage set* which is the minimum number of sensor nodes, having maximum residual energy, for the maximum possible coverage. From the optimal coverage sets across the network, some of the nodes form the dominating coverage sets which are used for ensuring network connectivity toward the sink. To achieve this, the dominating coverage sets are derived from the optimal-coverage sets by selecting 1-hop and/or 2-hop nodes to ensure connectivity.

Analysis: In DCCA, the neighbor node discovery is done periodically by sending *hello* messages. Further, multiple messages are exchanged to determine the optimal and dominating-coverage sets across the network. This message exchange could lead to energy wastage. The active nodes in the dominating-coverage set, preserve connectivity and forward data traffic to/from the sink node. Thus, the nodes closer to the sink node may drain their battery faster due to the *cascading effect* (similar to CLD (Yen et al., 2007)). Due to this, the node and network lifetime reduces. DCCA, avoids *coverage voids* due to the perimeter, center and distance tests. However, the wake-up rate of the sleeping nodes is not optimized. Sleeping nodes wake-up periodically to determine coverage contribution using optimal coverage set. The author's simulation setup for performance evaluation of DCCA is described as follows: area (A) = 250 m × 250 m, sensing range varies from 15 m to 40 m, transmission range of 100 m, packet length 100 bytes and buffer size of sensor nodes as 50. The performance evaluation of DCCA shows that, for low-density network up to 100 nodes, only 50% of the nodes are active and remaining nodes can enter into sleep state. Thus, the network lifetime of DCCA is prolonged by 28% (for low-density network (N = 100)) which indicates that, effective energy saving is achieved using coverage and dominating sets. As the sensing range of the nodes is increased (almost doubled), the number of redundant nodes increases by 70% which means that the number of active nodes required reduces by a large number.

3.1.7. Coverage and energy strategy for wireless sensor networks

Nam-Tuan et al. have presented CESS (Le and Min Jang, 2015) protocol for area coverage. CESS protocol operates in two phases where each sensor node operates in four states: INITIAL, WORKING, SLEEPING, and CHECKING. In the first phase, initially, all nodes operate in WORKING state. Each WORKING node exchanges its location information with its neighbor nodes. Then, each WORKING node estimates the *coverage contribution* with its neighboring WORKING nodes. The calculation of *coverage contribution* is similar to DCCA. If the *coverage contribution* is independent or WORKING node becomes redundant, then WORKING node enters into SLEEPING state. Else, it enters into WORKING state. In the second phase of CESS, nodes try to exchange their duties between SLEEPING and WORKING states based on coverage and connectivity conditions. The nodes in SLEEPING state wakes up periodically and enters into CHECKING state. The WORKING node enters into SLEEPING state if its neighbor CHECKING node has more residual energy level.

Analysis: CESS determines redundant WORKING nodes while preserving coverage. The protocol guarantees coverage in case of dense node deployment. There is the possibility of *coverage redundancy* or coverage overlap similar to DCCA, as discussed in Fig. 5. Hence, higher number of active nodes would cause energy wastage while maintaining full area coverage. *Sensing void* is not present due to perimeter, center and distance tests. In CESS, ACTIVE sensor nodes are used for maintaining coverage as well as connectivity. For the case of network connectivity, the 2-hop transmissions would require higher energy as compared to 1-hop transmission. Due to this, nodes required for both coverage and connectivity may die prematurely. The author's performance evaluation of CESS shows that optimal coverage can be maintained by minimum number of ACTIVE nodes. The area coverage percentage is almost 100% in case of CESS as compared to *Redundancy*

Table 1 Comparative analysis for distributed coverage protocols (location unaware, deterministic sensing model and probe based). Data are extracted from respective papers.

Protocol	PECAS	CLD	RBSP	DCBSP	DCCA	CESS	DCTC_k
Performance parameters (2–4) and other parameters (1, 5–8)	As compared to PEAS					As compared to S-MAC and RRP protocol	As compared to EETC and LADCS
1 Number of deployed nodes and Area [A]	100–800 [50 m ∗ 50 m]	50–550 [100 m ∗ 100 m]	100 [50 m ∗ 50 m]	100 [50 m ∗ 50 m]	300 [250 m ∗ 250 m]	300 [50 m ∗ 50 m]	50 [400 m ∗ 400 m]
2 ACTIVE node count	15.25% (+)	13.33% (–)	35% (–)	38% (–)	10.12% (+)	12.5% (–)	40.6% (–)
3 Sensing area coverage	26% (+)	25% (+)	12.5% (+)	31.23% (+)	[DN]	100%	75% to 100%
4 Network lifetime	24% (+)	36.35% (+)	19% (+)	39% (+)	28% (+)	25% (+)	25.42% (–)
5 Node scheduling	Periodic; based on work time duration	Same as PEAS	Random based on residual energy	Optimized based on battery level	Periodic	Periodic and conditional	Periodic
6 Coverage degree (C_d)	$C_d = 1$	$C_d = 1$	$C_d = 1$	$C_d = 1$	$C_d = 1$	$C_d = 1$	$C_d = 1$
7 Failure probability	NC	NC	NC	NC	NC	NC	NC
8 Sensing void	present	Present	Present	Present	Not present initially	Not present initially	Present

*A = Area, NC = Not considered, DN = Data not available, (+) = Higher by, (–) = Lower by.

Reduction Protocol (RRP) (Islam et al., 2009) for a simulation of up to 6000 s. The network lifetime of CESS is 12.50% higher as compared to RRP. The maximum number of ACTIVE nodes remain same (approximately 40 nodes) for node density up to 300 in case of CESS whereas S-MAC requires higher number fo ACTIVE nodes (up-to 140). Thus, network lifetime of CESS is higher as compared to S-MAC and RRP.

3.1.8. Connected target k-coverage

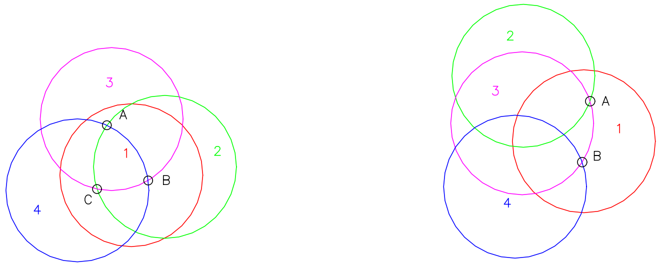
Jiguo Yu et al. have presented CTC_k (Jiguo Yu et al., 2016) for energy efficient coverage and connectivity in heterogeneous wireless sensor networks. CTC_k is further classified as Centralized Connected Target k-Coverage algorithm ($CCTC_k$) and Distributed Connected Target k-Coverage algorithm ($DCTC_k$). A node becomes ACTIVE in a connected coverage set (centralized or distributed) if it satisfies the following three conditions (1) the node has the chances of covering multiple targets by itself (2) the node has higher battery life (3) the node covers a target that is not k-covered by other sensor nodes in the existing selected set. If these three conditions are not satisfied then node can enter into sleep state. Further, each node in the cover set can communicate with the sink nodes by one or multi-hop neighboring nodes.

Analysis: In $CCTC_k$ and $DCTC_k$ the neighboring relay node can be used for connectivity. However, for monitoring k-coverage, multiple ACTIVE sensor nodes along with relay nodes for connectivity may increase energy consumption and reduce network lifetime. In CTC_k, if the central entity (sink node) fails, it can cause a communication failure within the network. There might be a possibility that for multiple rounds the same node could work as a relay node also. This may increase the energy consumption of this node which could lead to its premature death. Authors have compared CTC_k with EETC (Shih et al., 2009) and LADCS (Mostafaei and Meybodi, 2013) in terms of number of ACTIVE nodes, coverage sets and coverage degree. The author's performance evaluation using simulations shows that, the energy consumption for coverage degree (C_d) = 5, is almost 60% higher than that of C_d = 2. The average number of ACTIVE nodes for C_d = 1 is 5 times lesser than that of C_d = 6 in order to monitor 100 targets within the field. The average number of active nodes is higher by 30% to 90% as compared to EETC and LADCS, when the number of sensor nodes, ranges from 100 to 800 and the coverage degree ranges from C_d = 1 to C_d = 5. In $DCTC_k$, when the coverage degree (C_d) increases from 1 to 6, then the number of coverage sets decreases from 80 to 15 in order to monitor 30 targets within the network field. Further, slightly lesser coverage sets are needed as the number of targets increases.

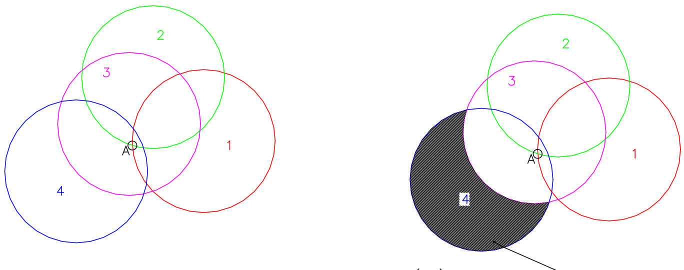
3.2. Comparative analysis of distributed, location unaware, deterministic sensing model and probe based coverage protocols

In this section, we have identified a few common performance evaluation parameters in order to compare the performance of distributed coverage protocols, discussed in earlier section. The protocols compared here are PEAS (Fan Ye et al., 2002), PECAS (Gui and Mohapatra, 2004), CLD (Yen et al., 2007), RBSP (More and Raisinghani, 2014), DCBSP (More and Raisinghani, 2015), DCCA (Tezcan and Wang, 2007), CESS (Le and Min Jang, 2015) and CTC_k (Jiguo Yu et al., 2016).

The performance measurement is based on ACTIVE node count, sensing area coverage and network lifetime. Table 1



(a) Node 1 can turn off (b) Node 1 can not turn off



(c) Node 4 can turn off (d) Sensing void in CCP

Figure 6 Sensing void in CCP.

shows the relative performance measurement of various coverage protocols. Table 1 shows, the quantitative analysis based on the data and coverage performance parameters which are discussed in the respective papers. This may help in the overall evaluation of coverage protocols while selecting a protocol for a particular application. We have kept PEAS as the reference protocol in order to evaluate the performance of other protocols.

PECAS has periodic scheduling, whereas in CLD, the wakeup rate of sleeping nodes is similar to PEAS. CLD uses deterministic node deployment due to which number of ACTIVE nodes are used. DCCA and CESS are based on *coverage computation test* which have perimeter, center and distance tests to determine the redundant sensor nodes. The *coverage computation test* ensures lesser voids within the network but at the same time it would tend to maintain higher number of ACTIVE nodes for monitoring the network field, as compared to other protocols.

$DCTC_k$ has higher network lifetime as compared to EETC and LADCS as shown in Table 1. The coverage degree (C_d) and node failure probability are incorporated only in PEAS whereas all other protocols do not provide $C_d > 1$ and do not handle node failure probabilities, as presented in Table 1. In PEAS, if the coverage degree $C_d = 3$ and node failure probability is 38%, then sensing area coverage of PEAS drops by 12–20%.

In the next section, we discuss coverage protocols which are distributed, location aware, use deterministic sensing model and computational geometry.

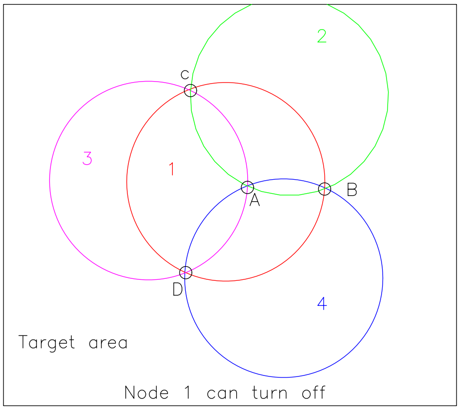


Figure 7 Turn off condition of ECCP.

3.3. Location aware distributed protocols

In this section, the *deterministic sensing model* represents the sensing range as a uniform well-defined circle (refer Section 2). CPP (Xing et al., 2005), ECPP (Zhang et al., 2009), PCP (Hefedda and Ahmadi, 2010), OGDC (Zhang and Hou, 2005) and PCPP (Sheu and Lin, 2007) are based on deterministic sensing model. However, CPP and PCP can also work on probabilistic sensing model. In the *probabilistic sensing model* sensing capability decreases with distance. There are different models available for probabilistic nature of sensing models such as exponential (Zou and Chakrabarty, 2005; Zou and Chakrabarty, 2004), polynomial (Liu and Towsley, 2004) or staircase (Ahmed et al., 2005). All of these techniques are based on computational geometry and assume static node deployment, that is, nodes do not move once they are deployed. In addition, these techniques assume that the node characteristics are identical. All the nodes are assumed to have location information, the same (and fixed) sensing coverage range, and same radio coverage range. The coverage and energy efficiency could be enhanced further by exploiting information about any geometric pattern existing in the network. Below we discuss coverage protocols which exploit this geometric information to enhance coverage as well as energy efficiency.

3.3.1. Coverage configuration protocol

CCP (Xing et al., 2005) is a decentralized protocol and assumes that each node has a uniform circular sensing range, with the node at center. It is also assumed that each node is aware of its location information accurately. CCP configures a network to the required coverage degree. Some of the applications require different degrees of sensing coverage, where every location of the region is monitored by more than one node. Other applications may require only one degree of coverage where only one node is sufficient for monitoring the region. In CCP, each of the nodes can be in one of the three states: *sleep*, *active* and *listen*. In the *sleep* state, the node turns off its radio to conserve energy. Each sleeping node periodically turns on and enters the *listen* state to determine whether it should continue to sleep or become active. In *active* state, the node actively senses the environment for events. The node uses a CCP *turn-off condition check*, to determine whether it should continue in the *active* state. A node turns itself off if it finds that the sensing range of a set of neighbor nodes overlaps with its own sensing range. The range overlap is determined by computing the intersection points within the node's sensing region. For example, as shown in Fig. 6(a), all intersection points within sensing the range of node 1 are covered by node 1's neighbor nodes(nodes 2,3,4), therefore, node 1 is eligible to turn off. In the case of Fig. 6(b), the intersection points A and B, inside sensing the range of node 1, are not covered by all of node 1's neighbor nodes(nodes 2,3,4). Intersection point A is covered by node 2 and node 3 but not node 4. Intersection point B is covered by node 3 and node 4 but not node 2. Therefore, node 1 is not eligible to turn off and it remains active.

Analysis: In CCP, each node needs to maintain a neighborhood table, so that it can determine the coverage overlap to check turn-off eligibility. Whereas, location unaware protocols, based on the probe, do not maintained neighborhood table for coverage redundancy. CCP turn-off eligibility algorithm can work for different coverage degrees, example $C_d \geqslant 1or2$, specified by an application. Active nodes may go back to sleep so that energy consumption is balanced among the nodes. Authors show that, if $R_c \geqslant 2R_s$ where R_c is communication range and R_s is sensing range. CCP requires the lesser number of active nodes. One of the major limitations of CCP is that it does not provides full coverage and it can create *sensing voids* as shown in Fig. 6(c) and (d). As shown in Fig. 6(c) the intersection point A in node 4 is covered by its all other neighbor nodes 1,2 and 3, therefore, node 4 is eligible to turn off. However, if node 4 goes into off state it could result in some area becoming uncovered as shown in Fig. 6(d). The authors have compared CCP with Ottawa (Tian and Georganas, 2002) and SPAN (Chen et al., 2002) protocols. Ottawa is a distributed area coverage protocol. SPAN is a power saving mechanism designed for multi-hop ad hoc wireless networks. CCP provides different *coverage degree* based on application requirements while Ottawa protocol does not support variable coverage degree. CCP shows a lesser number of redundant nodes as compared to SPAN. In CCP, there is 1% of patches which is 4-covered within the total sensing area whereas there are 80% of patches which are 4-covered in Ottawa protocol. This indicates that, CCP is efficient in controlling the number of redundant active nodes as compared to Ottawa. CCP is able to maintain full coverage (approximately 100%) for Rc/Rs ratio up to 2.5 whereas coverage ratio of SPAN decreases as Rc/Rs increases. In the next section, we discuss how Enhanced Configuration Control Protocol(ECCP) (Zhang et al., 2009) overcomes the *sensing void* problem of CCP.

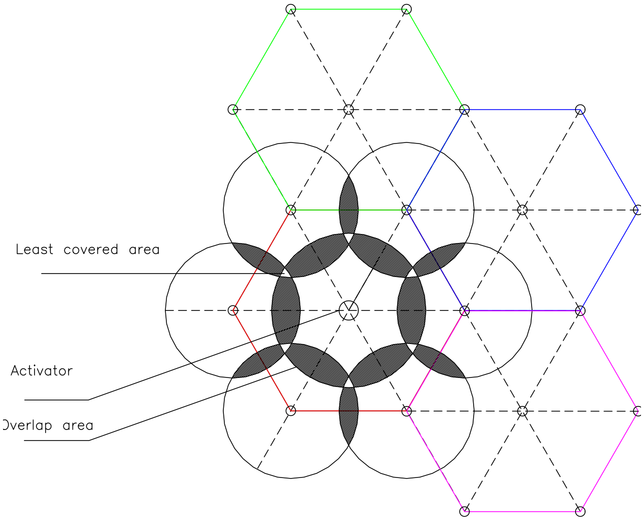


Figure 8 Node activation and formation of hexagonal pattern only in PCP.

3.3.2. Enhanced configuration control protocol

The existence of a sensing void in the coverage area of a wireless sensor network degrades coverage of a WSN. The CCP algorithm is unable to avoid sensing void as shown in Fig. 6 (c and d). ECCP (Zhang et al., 2009) algorithm provides a mechanism to avoid sensing voids in a network but, it takes more number of active sensor nodes. In ECCP, the logic of CCP is enhanced by adding the condition that boundaries of the target region are also covered by the neighboring nodes. Thus, in ECCP, a node can turn off only if it has intersecting points covered by neighbor nodes, node border range and the boundary of target region as shown in Fig. 7. The node states in ECCP are the same as in CCP as *SLEEP*, *ACTIVE* and *LISTEN*.

Analysis: ECCP ensures full coverage of the target area. ECCP ensures that there is no sensing void while, maintaining required number of active sensors. Energy consumption is balanced among the nodes as active nodes may enter into the sleep state. The number of sensing voids caused by CCP are more as compared to ECCP. One of the disadvantages of ECCP is that the number of active nodes is more than CCP because of ECCP's additional node turn off conditions (neighbor node, node border range and target region boundary). Authors show that for coverage degree (C_d) 1 or 2, the average coverage in case of ECCP and CCP is similar. However, CCP provides poor coverage when the coverage degree is greater than three ($C_d \geqslant 3$). The number of coverage voids caused by CCP is much more as compared to ECCP. The sensing voids reached up-to 8% when the number of nodes is less (up to 50) in an area of $50 * 50\,\text{m}^2$. However, the number of active nodes in case of ECCP is higher by 1–7% than that of CCP, due to the extra turn-off conditions.

3.3.3. Optimal geographical density control

OGDC (Zhang and Hou, 2005) is a density control algorithm that determines the minimum number of working nodes for full coverage. OGDC assumes that sensor nodes know their own location through localization methods (Ye et al., 2001; Cerpa and Estrin, 2004; Li et al., 2009). It is also assumed that sensor nodes are time synchronized. OGDC assumes that the communication range is at least twice the sensing range. In OGDC nodes can be in one of the three states: *ON*, *OFF*, and *UNDECIDED*. The algorithm runs in rounds. At the beginning of the first round, all nodes wake up, set their state to *UNDECIDED* and participate to select an active node based on a $turn - on$ condition. The first node of each round is randomly selected in a decentralized manner. A node can turn *ON* only if two conditions are met (i) it has the minimum possible overlapping area with at least two working nodes and (ii) when all the three nodes together are *ON*, there is sensing void in between the sensing range of these nodes. The aim is to maximize the coverage area, with minimal overlap, and avoids sensing void. By the end of execution of a round, all nodes change their states to either *ON* or *OFF* and remain in that state until the beginning of the next round. In OGDC message overhead is present for broadcasting location information to entire network at the beginning of each round. The interval of each round is set to approximately 1000 s.

Analysis: OGDC maintains coverage degree $C_d = 1$ when radio range is twice of sensing range. In OGDC overlap of sensing area is used as a parameter for switching off nodes for energy conservation. OGDC selects active nodes in each round. For each round, active nodes are different, therefore energy balance among nodes is possible. Through simulations, authors show that, PEAS and GAF (Ya et al., 2001), for a probing range of 9 m and area (A) = $50 * 50\,\text{m}^2$, required almost 50% more number of ACTIVE nodes as compared to OGDC for maintaining the same level of coverage (almost 100%). Sensing area coverage of OGDC is almost 100%, when the number of nodes (N) varies from 100–900 nodes. OGDC has 40% more network lifetime and 94% of sensing area coverage for node density of 100 as compared to GAF. In OGDC, lifetime is defined as the time duration for which area coverage percentage remains above a pre-determined threshold value, and coverage is provided in an area by at least one node ($C_d = 1$). OGDC, gives 98%-95%-90% - lifetime for probing range varying as 10 m–9 m–8 m respectively. OGDC has higher lifetime as compared to PEAS by 100% for probing range 10 m, 50% for probing range 9 m and 40% for probing range 8 m.

3.3.4. Probabilistic coverage protocol

PCP (Hefedda and Ahmadi, 2010) is a distributed coverage protocol. PCP can be applied to deterministic sensing model as well as probabilistic sensing model. PCP activates sets of nodes to form hexagonal structures in the field being monitored. An *activator*, which is any node in the network, activates other nodes which are located at vertices of a hexagon. This process continues till the activated nodes form a triangular lattice in the field, as shown in Fig. 8. PCP algorithm works in rounds. At the beginning of a round, each node selects a random startup time, depending on its remaining energy. At that selected point in time, the node goes to START state. The node which had selected the smallest time value will become active first. This node is known as an *activator*. The activator broadcasts activation messages within its communication range. A node receiving the activation message determines whether it is at the vertex of a hexagon, taking the activator as reference point (Hefedda and Ahmadi, 2010). Thus, PCP activates the nodes which are close to vert-ices of the hexagon in a distributed manner.

Analysis: PCP converges fast because it takes less time to determine the schedule of active/sleep nodes as compared to CCP and OGDC. The sensing void may not be possible in PCP due to the hexagonal structure based node selection in the field as compared to CCP. PCP is based on coverage degree ($C_d = 1$). PCP controls the density of activated nodes by turning on lesser active nodes, which have more energy reserves due to which PCP increases network lifetime. Authors compare PCP protocol with the probabilistic coverage protocol (CCANS) (Zou and Chakrabarty, 2004) and deterministic coverage protocols (OGDC and CCP), in terms of a number of activated nodes, network lifetime, and energy consumption in the network. PCP activates 50% lesser number of nodes as compared to CCANS while maintaining the same level of coverage (approximately 100%) within the network. CCANS activates higher number of nodes which could lead to higher number of message exchanges, as compared to PCP. Thus, in CCANS, node energy is depleted at a much higher rate as compared to PCP. For example, after 700 s, the average residual energy is 70% in case of CCANS to maintain coverage, while the average residual energy is 95% in case of PCP protocol. The network lifetime of PCP is almost 55% higher than that of CCANS. For the case of deterministic sensing model, PCP activates 38% lesser number of nodes as compared to OGDC and CCP. CCANS activates more nodes and exchanges more messages than PCP, thus energy depletion is at a faster rate. The average energy consumption of CCANS is 60% whereas PCP protocol requires on an average 10% energy consumption to maintain coverage similar to that of CCANS. The energy consumption of PCP is almost 42% lesser than CCP and 18% lesser than OGDC. In the next section, we discuss a centralized location aware protocol.

3.3.5. Probabilistic coverage preserving protocol

PCPP (Sheu and Lin, 2007) is a centralized, energy efficient coverage protocol. In PCPP, the base station broadcasts active/sleep schedule to each node. After receiving active/sleep schedule, each node becomes active or goes to sleep. PCPP works in rounds. In the first round, PCPP algorithm selects an unused sensor, based on the number of uncovered intersection points in the target region. If more than one sensor is present in the region then it selects a sensor which is covering lesser intersection points. If more than one sensor satisfies the first and second conditions then the algorithm selects the one which has more residual energy. If more than one sensor satisfies all the three conditions, then the algorithm chooses the one which has the smallest unique node ID. This process continues until it finds a sufficient number of unused sensors, for adequate coverage.

Analysis: PCPP is an energy efficient coverage preserving protocol. PCPP can be used for $C_d > 1$. PCPP uses a centralized algorithm and hence it faces the problems of any centralized approach. For example, failure of the entity running node selection algorithm would cause failure of PCPP. PCPP selects the minimum set of active nodes for energy conservation and maintains full coverage for the complete area. Simulation setup is described as $120 \times 120\ \text{m}^2$ square region. Each node has the sensing range of 10 m and communication range of 25 m. Each nodes lifetime is assumed as 50 min if it is active all the time. Authors show that, PCPP requires lesser number of active nodes as compared to CCP (Xing et al., 2005) because PCPP algorithm is not only based on intersection points but also on residual energy. If CCP has 50 ACTIVE nodes then PCPP maintains 38 ACTIVE nodes which indicates that PCPP maintains 31% lesser ACTIVE nodes than that of CPP for $C_d = 1$. Similarly, for the case for $C_d = 2$, PCPP maintains 42 ACTIVE nodes whereas CCP maintains 56 ACTIVE nodes which indicates that 33% lesser ACTIVE nodes as compared to CCP.

3.3.6. Balanced energy and coverage guaranteed protocol

Nam et al. have developed a BECG (Le et al., 2013) for coverage and energy efficiency. Each node in BECG protocol has three states: SLEEPING, CHECKING and WORKING. In BECG, SLEEPING node wakes up and goes to CHECKING state and waits for CHECK messages, to identify the presence of any *exchange node* in its neighborhood. Here, for a SLEEPING node, the WORKING node is an exchange node and vice versa. The WORKING node goes to CHECKING state if it finds any exchange node in its neighborhood. This CHECKING node broadcasts CHECK messages containing its current energy level to all its neighbors. Any neighbor WORKING node receiving this CHECK message determines the *coverage redundancy* or *coverage contribution* similar to DCCA (Tezcan and Wang, 2007). However, the determination of optimal and dominating coverage sets is not determined in BECG. If a WORKING node finds itself to have redundant coverage then it enters into SLEEPING state. Else, it remains in WORKING state for a fixed time period. Any SLEEPING node which receives the CHECK message enters into the WORKING state if the SLEEPING node energy level is 20% more than that of the CHECKING node's energy level. Else, it enters back into SLEEPING state.

Analysis: In BECG protocol, WORKING nodes exchange their duties with neighboring SLEEPING nodes and vice versa periodically. *Coverage void* is avoided but there is possibility of *coverage redundancy* as explained in Fig. 5. Therefore, optimal count of WORKING nodes is not maintained by BECG which increases energy consumption. Authors have not addressed the issue of connectivity between the nodes while determining coverage contribution. BECG is location aware protocol. The authors have compared BECG with S-MAC (Ye and Estrin, 2004) and Redundancy Reduction Protocol (Islam et al., 2009), using simulations. The ACTIVE node count of BECG is linearly increasing with an increase in node density as compared to RRP and S-MAC. BECG shows 40% higher network lifetime as compared to S-MAC and RRP. The sensing area coverage of BECG is 8–10% higher than that of RRP and S-MAC.

3.3.7. Edge based centroid algorithm

Aliyu et al. have proposed EBC (Aliyu et al., 2016) algorithm which enhances the area coverage using limited node mobility. The EBC algorithm is based on *voronoi diagram* that is used to partition the sensing area into polygons. Each polygon consists

Table 2 Comparative analysis for distributed coverage protocols (location aware, deterministic sensing model and probe based). Data are extracted from respective papers.

Protocol	ECCP	PCP	PCPP	OGDC	BECG	EBC
Performance parameters (2–4) and other parameters (1, 5–8)	As compared to CCP			As compared to PEAS	As compared to S-MAC and RRP	As compared to Min, Max, Vertex, VOR, Centriod
1 Number of deployed nodes and Area [A]	100–600 [50 m ∗ 50 m]	20,000 [4 km ∗ 4 km]	700 [100 m ∗ 100 m]	100–1000 [50 m ∗ 50 m]	120 [100 m ∗ 100 m]	20–50 [50 m ∗ 50 m]
2 ACTIVE node count	2% (+) for $C_d = 1$; 7% (+) for $C_d = 2$	38% (−)	31% (+)	20% (−)	52% (+)	11% (+)
3 Sensing area coverage	[DN]	4% (+)	[DN]	2.12% (+)	8% to 10% (+)	78% (+)
4 Network lifetime	[DN]	42% (+)	[DN]	12% (+)	40% (+)	21% (+)
5 Node scheduling	Based on eligibility test	Periodic	Conditional Probability based	Periodic; based on coverage redundancy	Conditional; based on energy and coverage contribution	Non-periodic; based on area coverage of local polygon
6 Coverage degree (C_d)	$C_d = 1$ and 2	$C_d = 1$	$C_d = 1$ and 2	$C_d = 1$	$C_d = 1$	$C_d = 1$
7 Failure probability	NC	NC	NC	NC	NC	NC
8 Sensing voids	Not present	Not present	Present	Not present; Initially	Not present; Initially	Present

*A = Area, NC = Not considered, DN = Data not available, (+) = Higher by, (−) = Lower by.

of only one sensor node which could monitor an external event. In the first stage of EBC algorithm, nodes broadcast their location information within their neighborhood. Based on location formation, each node calculates the bisectors of their neighbors and themselves to construct a *voronoi polygon*. After that, each node checks its local/own polygon for any possible coverage holes using simple geometric computation. If any coverage hole exists, then sensor node identifies a new location in order to reduce the coverage hole. The new location is determined using *Polygon Edge Midpoints Calculation*. Once the new location has been determined, then the current location of the node is compared to the new location, if there is an increase in area coverage of the sensor node then node moved to the new location or else maintained its current position.

Analysis: Authors have not discussed any scheduling mechanism for the nodes. This may lead to coverage redundancy in case more than one node remains ACTIVE in the polygon due to random deployment. In EBC, node mobility essential to ensure energy efficient coverage. However, the algorithm does not discuss energy consumption related to node movement. The performance evaluation of EBC shows that, EBC has higher area coverage increasing from 78% with 25 nodes to 99% with 60 nodes as compared with existing methods such as VEDGE, Maxmin-Vertex, Maxmin-Edge, Minmax-Edge, Minimax, and VOR. The average energy consumption of EBC algorithm for 100 runs is lower as compared to existing methods, it shows that EBC has 21% lower energy consumption as compared to other methods. The convergence rate (rounds required for adequate area converge) of EBC is lower as compared to other methods due to which EBC has higher energy efficiency.

3.4. Comparative analysis of distributed, location aware, deterministic sensing model, computational geometry based coverage protocols.

In this section, we have done the comparative analysis of coverage protocols (CCP, ECCP, PCP, PCPP, OGDC, BECG and EBC) based on performance evaluation done by authors in their respective papers. Our analysis is based on ACTIVE node count, sensing area coverage, energy consumption, similarly, other parameters such as coverage degree and node failure probability are also discussed in Table 2.

PCP has higher coverage (almost 100%) and network lifetime as compared to CCP, ECCP and PCPP protocol. PCP is based on hexagonal structure where ACTIVE nodes are present at the vertex of each hexagon. Due to this, PCP maintains adequate count of ACTIVE nodes. ECCP incorporates an extra turn-off condition along with the CCP mechanism, to avoid sensing voids. Due to this, higher number of ACTIVE nodes are required in ECCP. The performance of ECCP is higher in terms of ACTIVE node count for coverage degree 1 and 2, as compared to CCP. PCPP and ECCP provide variable coverage degree – ($C_d = 1$ or 2) whereas other protocols have coverage degree ($C_d = 1$). In addition, CPP supports coverage degree ($C_d = 1 - 6$), based on application requirement. OGDC uses *coverage overlap* as a parameter for scheduling the nodes periodically. Thus, network lifetime is higher as compared to PEAS. Node failure probability is not handled by any of these coverage protocols.

In the next section, we discuss coverage protocols which use clustering, location information, deterministic sensing model and probe mechanism.

3.5. Location aware clustering protocols

Many research efforts have been made to exploit the energy efficient coverage using clustering protocols in WSN. These clustering protocols are classified according to their objectives (Yu and Chong, 2005) such as *Dominating Set Based Clustering*, *Low Maintenance Clustering*, *Mobility Aware Clustering*, *Load Balancing Clustering* and *Energy Efficient Clustering*. In this paper, we have reviewed and focused only on the energy efficient clustering techniques used in WSN for energy efficient coverage.

3.5.1. Energy and coverage-aware distributed clustering protocol

Xink et al. presented the ECDC protocol (Gu et al., 2014). ECDC uses area/point coverage for energy efficiency. ECDC protocol works in rounds. Each round contains cluster set-up section and data transmission section. In cluster set-up section, ECDC protocol schedules the sensor nodes to work as either cluster head, cluster member or plain node, based on LEACH (Wendi et al., 2002) protocol with additional *coverage metrics*. These additional coverage metrics are area/ point coverage and residual energy. In ECDC protocol, different coverage importance metrics are designed for different applications. Here, the nodes with higher energy level and smaller coverage importance are selected as cluster heads. In the data transmission section, ECDC protocol adopts multi-hop forwarding mechanism for inter-cluster communication.

Analysis: ECDC protocol uses randomized rotation of cluster head within the clusters, in each round, for energy balancing. However, ECDC cannot ensure energy balancing as the cluster heads are elected based on random probabilities without considering the residual energy (Wendi et al., 2002). Therefore, the sensor nodes which have lesser amount of residual energy may be elected as cluster heads. Due to this, nodes may die prematurely as compared to other sensor nodes which have higher residual energy level. Further, this could create *coverage voids* within the network. In ECDC, authors have not addressed, the need for re-election of cluster heads before timeout of current round. This situation could occur due to accidental failure of an existing cluster head which would lead to a coverage void and could disrupt network connectivity. In addition, communication between cluster heads would require transmission over longer distance which would lead to energy wastage. Further, the sensor nodes which are closer to the cluster heads could face the *cascading effect*, similar to CLD (Yen et al., 2007), and hence could get drained faster. The performance evaluation of ECDC, LEACH, HEED (Ossama and Sonia, 2004) and EADC (Nokhanji et al., 2014) is done by the authors using two scenarios- random node deployment and non-uniform node deployment. The network lifetime of ECDC is higher in the non-uniform scenario, where the improvements are 62%, 31% and 6% compared with LEACH, HEED and EADC respectively. In the non-uniform scenario, the improvements are 46%, 25% and 12%, respectively. The area coverage performance of ECDC, EADC, HEED and LEACH is 98%, 76%, 65% and 50% respectively, for 50 rounds of election.

3.5.2. Area of interest

Mishra et al. have proposed a solution to monitor the *Area of Interest* (AoI) (Misra et al., 2011), while maintaining sufficient count of active nodes in the subset. The mechanism is based on *Euclidean Distance-Based Coverage* scheme, which calculates the overlap area between sensor nodes in the monitoring field. In AoI, the total network field is divided into clusters, where all nodes in a cluster can communicate with a deployed cluster head. The cluster head broadcasts a HELLO message and starts a timer (*Twait*). After receiving the HELLO message from the cluster head, the neighboring nodes send their node identifier and location information to the cluster head. The cluster head updates its database with this information. After *Twait* expiry, the cluster head stops listening to the sensor nodes within its cluster. Based on this information, the cluster head partitions the cluster into disjoint sets to ensure adequate coverage. Once the cluster head divides the nodes into sets, it sends the set number and work time *Twork*, to all the nodes. Nodes in a set become active or remain asleep for the time *Twork*. Later, the active nodes go to sleep.

Analysis: Due to the division of network field into sets for the AoI, there is a possibility of incomplete coverage. Thus, full coverage, over the entire network, may not be maintained by the AoI approach. In addition, communication between multiple sets and forwarding of aggregated data toward the cluster head may lead to increase energy consumption. The AoI approach does not handle the failure of cluster heads due to which *coverage void* of an entire set could get created and network partition could be possible. The node scheduling within the set is periodic and based on *Twork* allocated by a cluster head. This periodical *Twork* increases the wake-up rate of sleeping nodes which could increase the energy consumption in the network. The authors' simulations show that, the average area coverage percentage of the first set is about 95% while it is around 90% (ranging from 95% to 86%) for second and third sets. Similarly for the last or fourth set it is 75% (ranging from 70% to 80%). This is due to the nodes getting used up in the initial sets. The later sets have lesser number of nodes and thus lesser coverage. The author's simulation results also show that, the energy consumption 4.5 mJ per unit area per unit sensing time irrespective of the coverage area or the number of active nodes.

3.5.3. Energy efficient protocol for coverage, connectivity and communication

Akhlaq et al. have proposed an integrated and energy-efficient protocol for Coverage, Connectivity and Communication (C3) (Akhlaq et al., 2014). C3 protocol runs in six steps. 1. *Formation of rings*: The C3 protocol divides the network into virtual concentric rings, based on the communication range (R_c), using *RSSI* distance estimator. 2. *Formation of clusters*: A cluster head is selected alternately from even or odd numbered rings, in a *round*. 3. *Formation of dings*: A ding is a subsection of ring with a cluster head. The cluster head identifies the nodes which are at the distance of $\sqrt{3}R_s$ to form the ding. Therefore, there might be multiple dings inside a ring. 4. *Identification of redundant nodes*: C3 protocol uses *triangular tessellation* based on R_s inside the dings to identify redundant nodes. The redundant nodes can enter into sleep state for a time duration of T. 5. *Establish connectivity*: C3 protocol establishes connectivity between neighboring nodes and cluster head. 6. *Communication*: Finally, in C3 protocol data are transmitted to the sink node with the help of cluster heads.

Analysis: C3 protocol provides partial coverage in case there is unavailability of nodes at required position (triangular tessellation). Hence, C3 does not guarantee full area coverage. The death of cluster heads would cause connectivity and communication failure in the network. In addition, this failure can also lead to *coverage voids* in the multiple dings within a ring. In C3, the cluster heads decrease with increase in the ratio of $\frac{Rc}{Rs}$. The authors have shown that, C3 protocol maintains lesser number of active nodes as compared to CCP (Xing et al., 2005) and *Layered Diffusion-based Coverage Control (LDCC)* (Wang et al., 2007) protocols. Thus, the coverage lifetime of C3 is higher as compared to CCP and LDCC protocols. However, C3 protocol works in rounds with periodic execution of triangular tessellation. This may increase energy consumption and reduce network lifetime. The simulation results in term of

Table 3 Comparative analysis of clustering based coverage protocols (location aware, deterministic sensing model and probe based). Data are extracted from respective papers.

Protocol	ECDC	AoI	C3	CACP
Performance parameters (2–4) and other parameters (1, 5–8)	As compared to LEACH, HEED, EADC		As compared to LDCC and CCP	As compared to CPCP
1 Number of deployed nodes and Area [A]	100 [200 m ∗ 200 m]	100 [50 m ∗ 50 m]	50–500 [50 m-500 m ∗ 50 m-500 m]	100–1000 [120 m ∗ 120 m]
2 ACTIVE node count	50% (+) as compared to LEACH	on an avg. 18 nodes for 80 sets	51% (–) as compared to CCP	60% (+) by CPCP for 1000 round
3 Sensing area coverage	48% (+), 32% (+), 22% (+)	70% to 96% for 80 sets	6% (+) by LDCC and 6% (–) by CCP	66% (+)
4 Network lifetime	62% (+), 31% (+), 6% (+)	4.5mj/node consumption	40% (+) by LDCC and 70% (+) by CCP	140% (+)
5 Node scheduling	Periodic and conditional	Periodic; based on cluster head	Periodic and coverage matrices	Conditional based on coverage matrices
6 Coverage degree (C_d)	$C_d = 1$	$C_d = 1$	$C_d = 1$	$C_d = 1$
7 Failure probability	NC	NC	NC	NC
8 Sensing voids	Present	Present	Present	Not present initially

*A = Area, NC = Not considered, DN = Data not available, (+) = Higher by, (–) = Lower by.

Table 4 Summary of Coverage protocols with respect to methods, strength and weakness.

Protocol	Method	Strength	Weakness
PEAS	Probe based; poisson distribution	No neighbor node information	Requires high node density; non-uniform energy consumption
PECAS	Similar to PEAS	Energy balance in network; no local state information	Overall low energy saving
CLD	Fixed deployment; based on PEAS	Reduces cascading effect	Deterministic node placement; sensing void
RBSP	Random sleeping window	Residual energy based probing	Randomness in sleep time; sensing void
DCBSP	Battery discharge curve based probing	Optimized wake-up rate	Sensing void; Low energy saving
DCCA	Computational geometry based; perimeter, center and distance test	No sensing void initially	Full coverage; coverage redundancy; higher energy consumption
CESS	Computational geometry based; similar to DCCA based on residual energy	No sensing void initially	Higher number of active nodes; higher energy consumption
EBC	Voronoi polygon; computational geometry based	No sensing void; Limited mobility	Coverage redundancy; energy loss in node movement
CCP	Computational geometry based; intersection points	Adjustable coverage degree; integrated coverage and connectivity ratio	Sensing void
ECCP	Similar to CCP with additional turn-off condition	No sensing void	Coverage redundancy; overall low energy efficiency
OGDC	Sensing coverage overlap	Decentralized; energy balance among nodes	Higher messaging overhead
PCP	Triangular tessellation	Full area coverage; energy Efficiency; probabilistic sensing model (Exponential); random node failure	Coverage void due to non availability of nodes at suitable position
PCPP	Centrally broadcast sleep schedule	Works for $C_d \geqslant 1$	Centralized algorithm
CCT_K	Target K coverage; battery life	Disjoint set of sensor nodes	Coverage redundancy; higher energy consumption; Central control; multi-hop connectivity
BECG	Computational geometry based, similar to DCCA	Residual energy based probing; no sensing void	Incomplete coverage; coverage redundancy; higher messaging overhead
ECDC	Coverage metrics based on residual energy	Probability based cluster head selection similar to LEACH; used for point and area coverage	Non-uniform distribution of cluster heads; multi-hop communication causes energy wastage
AoI	Euclidean distance-based coverage scheme	Coverage overlap as measuring parameter within set; activation of set based on Area of interest	Incomplete coverage due to multiple sets; higher message exchange overhead; coverage void
C3	RSSI distance based	Layered architecture; maintained connectivity	Partial coverage; multi-hop communication overheads
CACP	Cost metrics; layered self activation algorithm	No sensing void initially; reduced coverage redundancy	Multi-hop communication; higher messaging overheads; partial coverage

ACTIVE nodes indicate that after 1000 rounds, 75% of nodes remain ACTIVE in C3 while 24% of nodes are ACTIVE in LDCC and all nodes in CCP exhaust their energy. Further, for this scenario, C3 provides 92% of coverage, all the nodes in CCP die resulting in no coverage at all while LDCC provides 45% of coverage. The energy consumption of CCP and LDCC is much higher than C3. C3 consumes only 25% of total energy while LDCC consumes 75% and CCP consumes almost 98% of the total available energy.

3.5.4. Coverage-aware clustering protocol

CACP (Wang et al., 2012) presents the selection of cluster head and active nodes are based on coverage metrics. The coverage metrics are residual energy of node and percentage of sensing coverage area. CACP consists of six phases which are: *information update*, *head election*, *cluster formation*, *sensor activation*, *intra-cluster routing* and *data communication*. In the information update phase, each node exchanges its location and energy information with its neighboring nodes. The selection of cluster head is based on the residual energy level of nodes. After the cluster formation, all cluster heads are in an active state while the cluster members execute *rotated triangle tessellation* with the help of distance and angle information from neighboring nodes to identify redundant nodes. If a node finds that its own sensing area has coverage redundancy less than a required threshold value, then it declares itself as an active node till the expiry of an *activation timer*. Else, it enters into sleeping state.

Analysis: In CACP protocol, there might be loss of coverage and connectivity due to the failure of the cluster heads. The energy consumption of cluster heads is always high due to direct transmission of aggregated data toward base station which could cause early failure of the cluster heads. CACP does not guarantee full sensing area coverage as nodes may not be found at suitable locations (triangular tessellation). The proposed CACP protocol adaptively changes the node activation timer according to its coverage metric. The coverage metric indicates the amount of sensing area of a node that is covered by neighboring active nodes. If a sensor node has higher coverage metric, then its activation time is shorter.

Authors show that, the number of ACTIVE nodes are 64% higher as compared to CPCP (Soro and Heinzelman, 2009). The network lifetime is 25% higher as compared to CPCP for full area coverage. However, for 80% of area coverage, the network lifetime of CACP is 47% higher as compared to CPCP. Thus, CACP performs well in terms of network lifetime, coverage and number of ACTIVE nodes as compared to CPCP.

3.6. Comparative analysis of clustering, location aware, deterministic sensing model and probe based coverage protocols

In this section, we present the comparative analysis, based on performance evaluations done by authors in their respective papers. Table 3 shows, the comparative analysis for clustering protocols (ECDC, AoI, C3 and CACP). Our analysis is based on ACTIVE node count, total sensing area coverage and energy consumption within the network. The other parameters are also presented in Table 3 which are similar to that shown in the earlier Section 3.3 and 3.5.

ECDC has higher sensing area coverage and network lifetime as compared to LEACH, HEED and EADC protocols as shown in Table 3. This is due to, extra coverage metrics incorporated in ECDC along with cluster head selection based on LEACH protocol. In AoI, the total network field is divided into number of *coverage sets* where adequate number of ACTIVE nodes monitor the target within those sets. Thus, network lifetime of AoI can be represented in terms of coverage sets. The sensing area coverage provided by each coverage set varies from 70% to 96% of the area monitored by the set. C3 protocol provides better performance as compared to CCP and LDCC protocols as shown in Table 3. C3 provides higher coverage, greater than 90% as compared to CCP, based on RSSI distance estimator.

CACP has conditional scheduling based on metrics such as residual energy and coverage redundancy. Due to this, frequent and unnecessary wakeup of sleeping nodes, is avoided which leads to lesser energy consumption and increased network lifetime. The other parameters, coverage degree is one ($C_d = 1$) for all clustering protocols (ECDC, AoI, C3 and CACP). Similarly, node failure probability is not handled by any of these coverage protocols. ECDC and CACP do not allow sensing voids initially within the network. However, after some rounds of simulation, sensing voids could be present, due to energy depletion of node's batteries. In addition, AoI and C3 protocols provide partial sensing area coverage which could lead to creation of sensing voids within the network.

In the Sections 3.1, 3.3 and 3.5 above, we reviewed various energy efficient coverage protocols. We summarize the protocols in terms of their methods, weaknesses and strengths in Table 4. Interested readers may also refer to other energy efficient coverage protocols such as Geography Adaptive Fidelity (GAF) (Ya et al., 2001), Sponsor Area Algorithm (Tian and Georganas, 2002) and Coverage-Centric Active Nodes Selection (CCANS) (Zou and Chakrabarty, 2004). The metrics for coverage control algorithms and analysis of the relationship between coverage and connectivity is described in Zhu et al. (2012). Connected k-Coverage Working Sets Construction algorithm(CWSC) of coverage and connectivity for $C_d \geqslant 1$ is described in Yu et al. (2013). Xiang et al. (2011) estimate the number of nodes needed to cover an intended area with a connected network. It also provides a guaranteed degree of coverage and connectivity. In the next section, we discuss the open issues and future research directions for energy efficient coverage in sensor networks.

4. Open issues and future research direction

A number of issues arise while designing energy efficient sensor networks. In this paper, we surveyed existing energy efficient coverage and connectivity problems. A lot of challenges still exist. Below, we discuss some of the design parameters and the related future research directions for energy efficient coverage.

4.1. Limited node mobility

The coverage protocols (Fan Ye et al., 2002; Gui and Mohapatra, 2004; Xing et al., 2005; Zhang et al., 2009; Yen et al., 2007; Zhang and Hou, 2005; Cerpa and Estrin, 2004; Hefedda and Ahmadi, 2010) discussed in this paper assume that sensor nodes are static in nature, that is, the nodes do not move once they are deployed. Therefore, in order to improve the quality of coverage and connectivity, mobility of nodes should be considered. The mobility of sink node is discussed in Kamat et al. (2007) and limited mobility of nodes using dynamic coverage maintenance scheme is considered in Savvides et al. (2001). The existing mobility models, patterns and analysis of challenges caused by mobility, at the link layer, are discussed in Dong et al. (2013). Sekhar et al. (2005) describes Dynamic Coverage Maintenance (DCM) scheme with limited mobility of the sensor nodes to compensate the loss of coverage with the minimum expenditure of energy. In the references (Kamat et al., 2007; Savvides et al., 2001; Dong et al., 2013; Sekhar et al., 2005) the node mobility could help to achieve guaranteed coverage at all times in the network. This helps to reduce the sensing voids and it can also reduced the coverage overlap. The node mobility could be *random, constrained or predictable*. In case of random movement of nodes, nodes can move to all directions without considering the network challenges such as coverage redundancy, coverage void, energy consumption and network connectivity. For the case of controlled node movement, adequate coverage could be achieved. Predictable node movement follows certain patterns like lines, circles, predefined path, predefined sensor location with the help of sink node or base station. As discussed in EBC (Aliyu et al., 2016) the node movement to a new location is predictable and based on threshold value set for area coverage. Therefore, in EBC, the predictable node movement saves overall energy within the network as compared to other protocols. However, movement of nodes in a network could be a power consuming task. Depending on the node deployment or obstacles, the movement of one or more nodes could lead to cascading movement of many other nodes to ensure coverage. Thus, if large number of nodes are moved, the energy consumption in the network could be substantial. This could finally lead to coverage voids due to node failures. Therefore, based on application requirement detailed investigation is required to study the impact of mobility in WSN, for improving the quality of coverage, connectivity and overall network lifetime.

4.2. Location awareness

Awareness of the nodes' physical location is required by a number of coverage protocols discussed in Cerpa and Estrin (2004), Li et al. (2009), Zou and Chakrabarty (2004), Zhu et al. (2012), Yu et al. (2013), Le et al. (2013), Aliyu et al. (2016), Gu et al. (2014), Misra et al. (2011), Akhlaq et al. (2014) and Wang et al. (2012). The determination of relative node location information can be realized by utilizing directional antenna, and location identification techniques such as *RSSI distance estimator* which can be further classified as *received signal strength, time of arrival, time difference of arrival* and *angle of arrival* of signals. However, the performance of coverage protocols could be significantly affected due to moderate errors in distance estimates. Similarly, most of the sensor nodes assume a GPS module to locate the node location. However, adding a GPS module on the sensor node is not always feasible. The reasons are as follows. First, the module GPS requires line of sight to the GPS satellites. This may not be possible in case of deployment in a dense forest or, in some cases, on mountains. Second, the power consumption of GPS module would reduce the battery life of the sensor node and this, in turn, would reduce the network lifetime. Third, the size of GPS module may be large as compared to the size of the node. This could create deployment problems where the size of the node is crucial. On the other hand, location unaware protocols discussed in Fan Ye et al. (2002), Gui and Mohapatra (2004), Yen et al. (2007), More and Raisinghani (2014), More and Raisinghani (2015), Le and Min Jang (2015), Tezcan and Wang (2007) and Jiguo Yu et al. (2016) do not use information concerning the locations of nodes, probing range (Fan Ye et al., 2002; Gui and Mohapatra, 2004; Yen et al., 2007) or sensing range and REPLY received from current ACTIVE nodes to indirectly determine neighbor node position. In the case of location unaware protocols, the computation of coverage overlap is non-trivial. After deployment, the nodes are activated so as to maintain maximum sensing area coverage by keeping sufficient number of nodes in the ACTIVE state. However, due to the random deployment and location unawareness, there is a possibility of coverage redundancy or coverage void in the network. Hence, further investigation is required in order to determine accurate location information of nodes for adequate area coverage within the sensor network, ideally without a GPS device.

4.3. Heterogeneous network with obstacles

Most of the recent research work only considers homogeneous sensors which having similar technical characteristics and specifications (Fan Ye et al., 2002; Gui and Mohapatra, 2004; Xing et al., 2005; Zhang et al., 2009; Yen et al., 2007; Zhang and Hou, 2005; Cerpa and Estrin, 2004; Hefedda and Ahmadi, 2010; Zou and Chakrabarty, 2005; Zou and Chakrabarty, 2004; Ahmed et al., 2005; Liu and Towsley, 2004). However, some of the applications may require heterogeneous sensors having the different specification of nodes, with the aim to improve area coverage and network connectivity quality in an energy efficient manner. Further, uniform circular sensing and communication range may not always be a correct assumption. The range could take any shape due to environmental conditions such as interference, shadowing effects, signal strength and battery life etc. as discussed in Reichenbach et al. (2006) and Tan et al. (2010). To the best of our knowledge, existing coverage protocols do not adequately model the effect of variation in coverage ranges and obstacles. The coverage protocols (Fan Ye et al., 2002; Xing et al., 2005; Zhang et al., 2009; Yen et al., 2007; Zhang and Hou, 2005; Cerpa and Estrin, 2004; Hefedda and Ahmadi, 2010; Zou and Chakrabarty, 2005; Zou and Chakrabarty, 2004; Ahmed et al., 2005; Liu and Towsley, 2004) may not give realistic results due to the assumption of clear line of sight i.e. no obstacles. Due to this, sensing voids could be created. It could also leads to connectivity issues within the network. Further, research is required to develop and enhance protocols to address the effects of heterogeneous nodes and the presence of obstacles on coverage and network lifetime.

4.4. Optimized wake-up rate of sleeping nodes

Most of the work till date has not focused on optimal node scheduling. The coverage protocols discussed in this paper have different wake-up rate of sleeping nodes. The wake-up rate could be periodic, random, probability based, or based on coverage metrics. Periodic wake-up rate is discussed in Gui and Mohapatra (2004), Tezcan and Wang (2007), Jiguo Yu et al. (2016), Xing et al. (2005), Zhang et al. (2009), Zhang and Hou (2005) and Hefedda and Ahmadi (2010), random wake-up is presented in Fan Ye et al. (2002), Yen et al. (2007) and More and Raisinghani (2014), conditional wakeup rate based on coverage metrics is discussed in Cerpa and Estrin (2004), Li et al. (2009), Zou and Chakrabarty (2004), Zhu et al. (2012), Yu et al. (2013), Le et al. (2013), Aliyu et al. (2016), Gu et al. (2014), Misra et al. (2011), Akhlaq et al. (2014) and Wang et al. (2012) probability based wakeup rate is discussed in Sheu and Lin (2007) and discharge curve based wake up is discussed in More and Raisinghani (2015). However, there might still be a possibility of frequent and unnecessary wake-ups of sleeping nodes which could cause the wastage of energy. For example, nodes may consume energy at different rates depending on the network activity. Further, the rate of consumption may be fixed. The sleeping node wakeup mechanism should be able to handle such variations. This is an open research area.

4.5. Node failure probability

Now-a-days sensor networks are used for various practical applications. For example, assume that we want to monitor some contaminated environment, where manual sensor nodes placement may not be possible. Thus, some flying devices like unmanned helicopters could be used to drop sensor nodes from a higher altitude. In such a case, dropping the sensor nodes from a high altitude could cause the failure of some of the sensor nodes. In this scenario, the initial node failure probability could be high and needs to be considered at the time of deployment. Further, node failure could occur due to physical damage of components, hardware failure, and some extreme environmental conditions like the increase in temperature, pressure and humidity. This failure of nodes could cause *coverage voids* within the network and reduce the network lifetime. None of the existing coverage protocols consider the failure probability of nodes. PEAS and PCP have incorporated failure probability using a *random function* in order to determine the impact on ACTIVE node count, area coverage and coverage lifetime of sensor network. However, a detailed investigation is required to handle the failure probability of nodes while ensuring adequate coverage.

4.6. Optimized clustering techniques

Most of the recent research work considers random deployment of nodes. Many energy efficient coverage protocols have been proposed based on clustering (Gu et al., 2014; Misra et al., 2011; Akhlaq et al., 2014; Wang et al., 2012). In these protocols, the network field can be partitioned into various clusters. However, these methods are not without problems. In the clustered network, nodes do not consume energy at the same rate: the cluster head consumes more energy than a cluster member. Therefore, the death of a coverage-critical node may lead to coverage void in the networks. Thus, an improved mechanism could be proposed for selection of optimal cluster heads and cluster size which would balance the energy consumption and maintain sufficient coverage in the network.

4.7. Non-uniform distribution of initial battery level of nodes

The coverage protocols discussed in this paper have a uniform energy model. i.e. all deployed sensor nodes have same initial energy level or battery power. In such case, the energy distribution within the network could be uniform due to the same initial battery potential. However, this may not be a realistic approach, since the node batteries used in sensor network for real-time applications may not have the same initial battery potential. Thus, for the case of real-time application, at the time of deployment, the initial energy levels of the sensor nodes could be different due to different battery potential. Thus, to address this non-uniform distribution of initial energy levels, existing coverage algorithms could be improved or new coverage algorithm could be proposed.

4.8. Coverage degree

Coverage degree indicates redundant coverage in an area covered by sensor nodes. For example, in the deterministic sensing model, coverage degree refers to how many sensor nodes cover a *fraction of an area*. Using more than one sensor to cover a fraction of an area can improve the coverage robustness. If the fraction of an area is covered by k sensors, then it can tolerate up to $k-1$ failed sensor nodes. Therefore, we can state that higher the coverage degree lesser the possibility of *coverage voids* in the network. However, higher coverage degree increases the *coverage redundancy* in the network which causes energy wastage. Therefore, coverage degree is one of the important parameters while designing an energy efficient coverage protocol. The coverage degree could be based on application requirements and could also vary across the entire area to be monitored. Literature exists for addressing the k-coverage problem (Lin et al., 2013; Yu et al., 2012) based on game theory and *Pure Nash Equilibrium* in hybrid sensor networks. However, if an application requires adaptive coverage in the network field then existing algorithms may not be able to address the requirement. It is essential to create an algorithm that adapts locally to the coverage need, rather than have a fixed coverage degree.

5. Conclusion

Coverage redundancy in wireless sensor networks can be reduced by different coverage optimization protocols. In this paper, we provided a brief introduction and basic knowledge of coverage concepts used in sensor networks. We have taken energy efficient coverage protocols based on *area coverage* into consideration, and described the working mechanism of coverage protocols with an in-depth analysis. The objective of the coverage protocols is to keep a necessary set of working nodes *on* while turning *off* the redundant nodes for effective coverage and energy efficiency. Energy conservation can be achieved by reducing coverage overlap and optimal node scheduling which would increase the node and network lifetime. Our analysis of the existing energy efficient coverage protocols is based on the coverage mechanism (clustering/distributed), node scheduling mechanism, ACTIVE node count, coverage void, coverage redundancy computation, node failure probability and node, network lifetime. Finally, open issues for energy efficient coverage in WSNs are summarized. Further research is required to handle these parameters in an accurate manner which could improve the coverage and energy efficiency in sensor networks. Our analysis can be used as a starting point for future research in WSN coverage.

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