International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

A Survey on Cooperative Geographic Routing & Its Optimization in Wireless Sensor Networks

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Abstract: ***In this paper we begin with introduction to wireless sensor networks, its application, challenges in wireless sensor networks and different types of routing protocols. Cooperative geographic routing protocol works on node cooperation, which is one unique feature distinguishing wireless sensor networks from conventional wireless networks. Further we study a cooperative routing in coalition-aided wireless sensor networks and exploration of the new communication paradigm i.e., cooperative data transport, where sensor nodes within a coalition cooperatively transmit data via a three-phase procedure. We then see how the routing path selection is treated as multi-stage decision problem, where at each stage the coalition head would choose the next hop destination to minimize the corresponding energy consumption. Comprehensive study concludes that the optimal cooperative routing, where neighboring nodes dynamically form coalition and cooperatively transmit the packets to the next hop destination. Also the cooperative sensor network can be modeled as an edge-weighted graph, based on which minimum energy cooperative routing is characterized by using the standard shortest path algorithm.***

Keywords: cooperative sensor network

1. Introduction

Wireless sensor networks are a trend of the past few years, and they involve deploying a large number of small nodes. The nodes then sense environmental changes and report them to other nodes over s flexible networks architecture. Sensor nodes are great for deployment in hostile environments or over large geographical areas. The sensor nodes leverage the strength of collaborative efforts to provide higher quality sensing in time and space as compared to traditional stationary sensors, which are deployed in the following two ways:

1) Sensors can be positioned far from the actual phenomenon, i.e. something known by sense perception. In this approach, large sensors that use some complex techniques to distinguish the targets from environmental noise are required.
2) Several sensors that perform only sensing can be deployed. The position of the sensors and communications topology is carefully engineered. They transmit time series of the sensed phenomenon to central nodes where computations are performed and data are fused.

A wireless sensor network is a collection of nodes organized into a cooperative network. Each node consist of processing capability (one or more microcontrollers, CPUs or DSP chips), may contain multiple types of memory (program, data and flash memories), have RF transceiver (usually with a single Omni-directional antenna), have a power source (e.g., batteries and solar cells), and accommodate various sensors and actuators. The nodes communicate wirelessly and often self-organize after being deployed in an ad hoc fashion. Currently, wireless sensor networks are beginning to be deployed at an accelerated pace. It is not unreasonable to expect that in 10-15 years that the world will be covered with wireless sensor networks with access to them via the Internet. This can be considered as the Internet becoming a physical network. Wireless Sensor Network is widely used in electronics. This new technology is exciting with unlimited potential for numerous application area including environmental, medical, military, transportation, entertainment, home automation and traffic control crisis management, homeland defense and smart spaces.

(a) Challenging Issues in Sensor Networks

Routing in sensor networks is very challenging issue due to several characteristics that distinguish them from contemporary communication and wireless ad-hoc networks. First of all, it is not possible to build a global addressing scheme for the deployment of sheer number of sensor nodes. Therefore, classical IP-based protocol cannot be applied to sensor networks. Second, in contrary to typical communication networks almost all applications of sensor networks require the flow of sensed date from multiple regions (sources) to a particular sink.

Third, generated data traffic has significant redundancy in it since multiple sensors may generate same data within the vicinity of a phenomenon. Such redundancy needs to be exploited by the routing protocols to improve energy and bandwidth utilization. Fourth, sensor nodes are generally tightly constrained in terms of transmission power, on-based energy, processing capacity and storage and thus require careful resource management.

2. Applications of Wireless Sensor Networks

In networking unattended sensor nodes are expected to have significant impact on the efficiency of many military and civil applications such as combat field surveillance, security and disaster management. These system process data gathered from multiple sensors to monitor events in an area of interest. For example, in a disaster management's setup, a large number of sensors can be dropped by helicopter. Networking these sensors can assist rescue operations by locating survivors, identifying risky areas and making the rescue crew more aware of the overall situation. Such application of sensor networks not only increases the efficiency of rescue operations but also ensures the safety of the rescue crew. On the military side, applications of sensor networks are numerous. For example, the use of networked set of sensors can be limiting the need for personnel involvement in the usually dangerous reconnaissance missions. There are many more applications of wireless sensor networks few of them are mentioned below:

1) **Environmental monitoring**
   Wireless sensor networks have been used to monitor the quality and pressure of hazardous gases in landfills. Current methods of monitoring a landfill includes drilling and collecting gas samples, then analyzing them offsite. This is a time consuming and resource intensive process. Instead embedding wireless sensor in the landfill will provide live information about the gas levels at the landfill. Permanence is good example where wireless sensors have been deployed in the Alpine mountains to sense warming and thawing of permafrost.

2) **Body area networks**
   Collection of wireless sensors designed to capture specific data from the human body such as hemoglobin, blood sugar level, temperature, heart rate, movement etc. in a non-invasive manner are gaining popularity with health and biomedical professionals. Wireless sensors offer distributed and comprehensive monitoring while not inconveniencing the patient.

3) **Home automation**
   As technology advances, smart sensor nodes and actuators can be buried in appliances, such as vacuum cleaners, micro-wave ovens and refrigerators. These sensor nodes inside the domestic devices can interact with each other and with the external network via the Internet or Satellite. They allow end users to manage home devices locally and remotely more easily.

4) **Other commercial applications**
   Some of the commercial applications are monitoring material fatigue, building virtual keyboards, managing inventory, monitoring product quality, constructing smart offices spaces, environment control in office buildings, robot control and guidance in automatic manufacturing environments, interactive toys, machine diagnosis, transportation, vehicle tracking and detection.

3. Overview of Routing Protocols in Sensor Networks

Sensor network nodes are often limited in battery capacity and processing power. Thus, it is imperative to develop solutions that are both energy and computationally efficient. Energy aware routing in sensor networks has received significant attention in recent years. Finding a good routing algorithm to prolong the network lifetime is an important problem, since sensor nodes are usually quite limited in battery capacity and processing power. For exactly the same reason, complex routing algorithms do not work well in the scenario, due to excessive overhead.

The ease of deployment, ad-hoc connectivity and cost-effectiveness of a wireless sensor network are revolutionizing remote monitoring applications. At the node level, data communication is the dominant component of energy consumption, and protocol design for sensor networks is geared towards reducing data traffic in the network. As sensor close to the event being monitored sense similar data, the focus of existing research has been to aggregate (combine, partially compute and compress) sensor data at a local level before transmitting it to a remote user called the sink. The number of nodes that sense attributes related to an event in a geographical region depends on the footprint of the event.

(a) Types of Routing Protocols

There are many routing protocols that are proposed for the problem of routing the data in wireless sensor networks. These routing mechanisms have considered the characteristics of sensor nodes along with the application and architecture requirements. Almost all of the routing protocols can be classified as data-centric, hierarchical or location based although there are few distinct ones based on network flow or QoS awareness.

1) Data-Centric Protocols

In many applications of sensor networks, it is not feasible to assign global identifiers to each node due to the sheer number of nodes deployed. Such lack of global identification along with random deployment of sensor nodes makes it hard to select a specific set of sensor nodes within the deployment region with significant redundancy. Since this is very inefficient in terms of energy consumption, routing protocols that will be able to select a set of sensor nodes and utilize data aggregation during the relaying of data have been considered. This consideration had led to data-centric routing which is different from traditional address-based routing where routes are created between addressable nodes managed in the network layer of the communication stack.

In data-centric routing, the sink sends queries to certain regions and waits for data from sensors located in the selected regions. Since data is being requested through queries, attribute based naming is necessary to specify the properties of data. SPIN [9] (Sensor Protocol for Information via Negotiation) is the first data-centric protocol, which considers data negotiation between nodes in order to eliminate redundant data and save energy. Later, Directed Diffusion has been developed and has become a breakthrough in data-centric routing. Then, many other protocols have been proposed either based on Directed Diffusion or following a similar concept.

Examples
Flooding and gossiping, Sensor Protocols for Information via Negotiation (SPIN), Directed Diffusion, Rumour Routing, Gradient-Based Routing, Constrained Anisotropic Diffusion Routing (CADR), ACtive QUery forwarding In SensoR nEtworks (ACQUIRE).

2) Hierarchical Protocols

Similar to other communication networks, scalability is one of the major design attributes of sensor networks. A single-tier network can cause the gateway to overload with the increase in sensors density. Such overload might cause latency in communication and inadequate tracking of events.

In addition, the single-gateway architecture is not scalable for a larger set of sensors covering a wider area of interest since the sensors are not typically capable of long-haul communication. To allow the system to cope with additional load and to be able to cover a large area of interest without degrading the service, networking clustering has been pursued in some routing approaches.

The main aim of hierarchical routing is to effectively maintain the energy consumption of sensor nodes by involving them in multi-hop communication within a particular cluster and by performing data aggregation and fusion in order to decreases the number of messages transmitted to the sink. Cluster formation is typically based on the energy reverse of sensor and sensor's proximity to the cluster head. LEACH [14] is one of the first hierarchical routing approaches for sensors networks. The idea proposed in LEACH has been an inspiration for many hierarchical routing protocols, although some protocols have been independently developed.

Examples
Low-Energy Adaptive Clustering Hierarchy (LEACH), Power-Efficient Gathering in sensor Information Systems (PEGASIS), Hierarchical-PEGASIS, Threshold sensitive Energy Efficient sensor Network protocol (TEEN), Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN), Energy-aware routing for cluster-based sensor networks (Younis et al).

3) Location-based Protocols

Most of the routing protocols of sensor networks need location information for sensor nodes. In most cases location information is needed in the order to calculate the distance between two particular nodes so that energy consumption can be estimated. Since, there is no addressing scheme for sensor networks like IP-addresses and they are spatially deployed on a region, location information can be utilized in routing data in an energy efficient way. For instance, if the region to be sensed is known, using the location of sensors, the query can be diffused only to that particular region which will eliminate the number of transmission significantly.

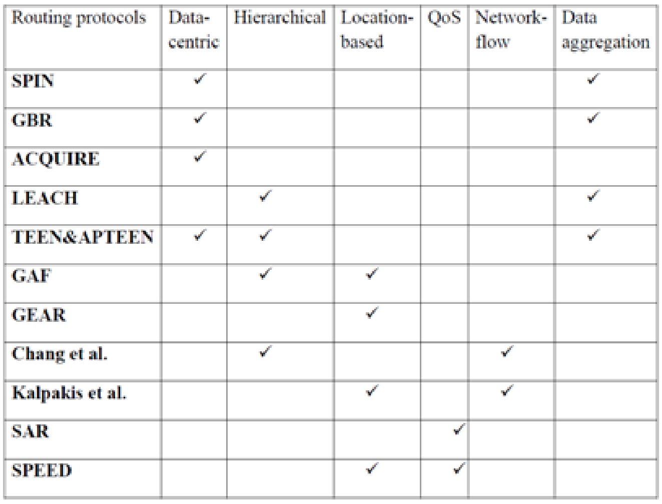
Examples
Minimum Energy Communication Network (MECN), Small Minimum Energy Communication Network (SMECN), Geographic Adaptive Fidelity (GAF), Geographic and Energy Aware Routing (GEAR).

4) Network Flow and QoS-aware Protocols

The last category includes routing approaches that are based on general network flow modeling and protocols that strive for meeting some QoS requirements along with the routing function.

Examples
Maximum lifetime energy routing: chang et al. Maximum lifetime data gathering Kalpakis et al. Minimum cost forwarding, Sequential Assignment Routing (SAR), Energy-Aware QoS Routing Protocol.

(b)Classification of Routing Protocols in Sensor Networks



Routing protocols	Data-centric	Hierarchical	Location-based	QoS	Network-flow	Data aggregation
SPIN	✓					✓
GBR	✓					✓
ACQUIRE	✓					
LEACH		✓				✓
TEEN&APTEEN	✓	✓				✓
GAF		✓	✓			
GEAR			✓			
Chang et al.		✓			✓	
Kalpakis et al.			✓		✓	
SAR				✓		
SPEED			✓	✓		

4. Cooperative Geographic Routing

According to [12], Routing in wireless sensor networks is challenging task due to dynamic network conditions and limited resources. Both geographic and non-geographic routing protocols have been developed for sensor network applications. Most non-geographic routing protocols are either proactive (to maintain route continuously), reactive (to create routes on demand) or hybrid. The performance of non-geographic routing protocol is degraded by the overhead necessary for route setup and maintenance. Geographic routing, with the knowledge of node location information, provides an alternative to route packets. It is also the groundwork of geocasting protocols and geographic-based rendezvous mechanisms [11].

The node cooperation techniques in wireless sensor networks have recently been shown to be efficient in terms of energy saving and performance again. By coordinating the transmissions from multiple sensors nodes to a common receiving node, the signal within the same channel from different nodes could be combined at the receiver to obtain stronger signal strength [4],[7]. Cooperation among sensor nodes provides a promising mechanism to exploit spatial diversity and reduce channel fading. This fundamental difference from the traditional point-to-point transmission model requires new routing protocols that can fully utilize the benefits of the new technology. This motivates us to take advantages of both node cooperation and geographic routing, and explore cooperative geographic routing for wireless sensor networks.

The term coalition is used to emphasize the cooperation among sensor nodes in a coalition. Different from traditional cluster-based networks, where the cluster head performs the bulk of communication tasks, in cooperative geographic routing the coalition head (CH) carries out data aggregation and coordinates the sensor nodes within coalition, but does not necessarily transmit data itself. This would improve the network performance by obtaining the cooperation gain, and reduce the hot-spot phenomenon at the CH.

(a) Coalition-aided Network Architecture

In coalition-aided network architecture, sensor nodes within cooperative data transmission. This architecture is motivated by the three key features of wireless sensor networks, namely node cooperation, data correlation and energy limitation.

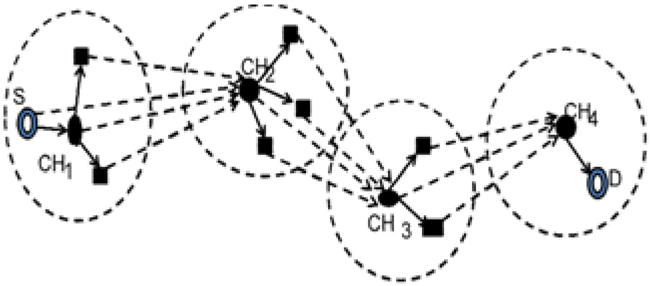


Fig.1 Coalition-aided cooperative geographic routing

As shown in above figure, all sensor nodes are grouped into coalitions following some clustering algorithm. Each node is either a CH, or a member node. Each coalition has unique CH, and all the nodes in one coalition are within the transmission range of the CH and a CH can communicate with CHs in neighbor coalitions. Different from traditional cluster-based architecture, the data at nodes within one coalition are highly correlated. Therefore, progressive data aggregation is needed to collect the most critical data from different sensors in an energy efficient manner. Moreover, the coordination is carried out by CHs, but the transmission is executed by all the nodes within a coalition, whereas in the traditional cluster-based model, they are performed by cluster heads.

Note that the overhead to setup and maintain the coalition-aided architecture is higher than that in the traditional cluster-based architecture, in the sense that the CH needs to coordinate the transmission. However, the benefits of the coalition-aided architecture are more significant

1) By allowing member nodes to participate in the transmission, the hot-spot problem in traditional cluster based network can be mitigated.
2) Data compression can be carried out within each coalition to reduce the total amount of data.

(b) Cooperative Data Transport with Coalition-Aided Architecture

Consider a wireless sensor network where the data packets are cooperatively forwarded from one coalition to another coalition via three phase process. Without loss of generality, consider the data forwarding process from coalition i to coalition k.

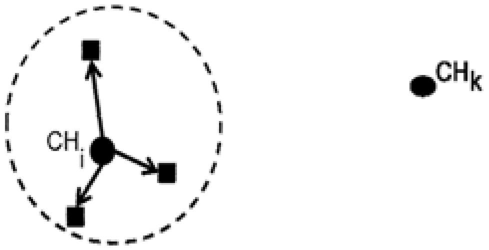


Fig. 1(a) Phase 1: CH_i broadcast the data to all nodes within coalition i.

Phase 1: CHi broadcasts the packets to all member nodes within this coalition using Point-to-multiple--point (broadcast) communication, as depicted in fig 1(a)

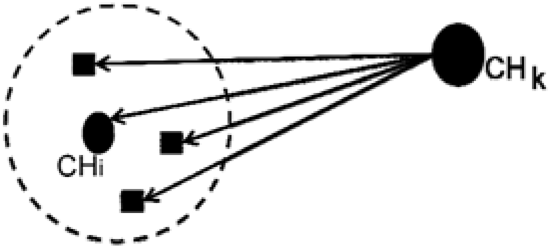


Fig.1 (b) Phase 2: CH_k broadcast pilot symbols to all nodes within coalition i.

Phase 2: To get the maximum throughput at each stage, it is desired to coherently combine the received signals. This requires the channel state information (CSI) to be known at the transmitter or receiver. At the beginning of each transmission the receiver broadcasts pilot symbols.

Phase 3: The node in coalition i would cooperatively forward the packet to Chk, which corresponds to a multiple-point-to-point (cooperatively) communication shown below:

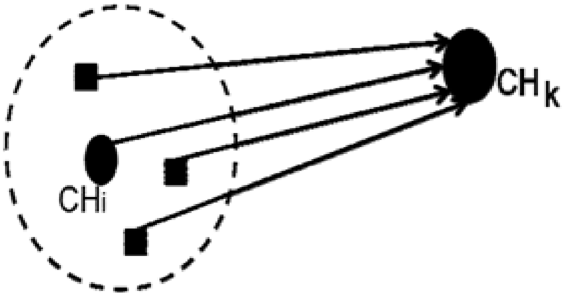


Fig. 1(c) Phase 3: nodes in coalition i cooperatively forward the data to $-CH_k$

(c) Energy Consumption Model

Let n_i denotethe number of nodes within coalition i. Then the received signal at CH_k is given by

$$\Upsilon_k(t) = \sum_{j}^{n_i} \alpha_{ik}^{j}\, s_{ik}^{j}(t) + \eta_k(t) \qquad (1)$$

Where α_{ik}^{j} is the channel gain from the jth node in a coalition i to the kth CH, $s_{ik}^{j}(t)$ is the transmission signal at node j, and $\eta_k(t)$ is the Guassian noise.

Assuming that each transmitter independently adjusts the power to contribute same amount of received power, the SNR at the k-th CH is givenby

$$\Gamma_{ik} = 1/N\left(\sum_{j=1}^{n_i} \sqrt{P}\right)^2 = n_i^2 P/N \qquad (2)$$

As is standard, assume that the SNR requirement to guarantee reliable transmission is

$$\Gamma_{ik} >= \gamma \qquad (3)$$

Then, the transmission power at node j is

$$P/(\alpha_{ik}^{j})^2 = \gamma N/(n_i\, \alpha_{ik}^{j})^2 \qquad (4)$$

this requires local information only.

Cooperative data transport can achieve better energy efficiency. For example if all channels gains are identically distributed, the average energy consumption of the cooperative transmission is 1/ni of that for the point-to-point transmission.

The total transmission power for coalition i is given by

$$C_{ik} = (\gamma N/n_i^2)\sum_j^{n_i} 1/(\alpha_{ik}^j)^2 \qquad (5)$$

Compared with the point-to-point transmission, where the cost is

$$C_{ik}^{|} = \gamma N/(\alpha_{ik})^2 \qquad (6)$$

Clearly, the number of nodes in a coalition plays a key role for energy consumption, whereas in traditional geographic routing, distance is the main metric to choose the next stage coalition. It can be seen from (5) that the more the nodes within one coalition, the less the energy consumption is.

(d) Overview of Point-to-Point Geographic Routing

In the early work of geographic routing as shown in [5], where it uses the node location information for route discovery. The most famous protocol in geographic routing is perhaps greedy forwarding, where each node forwards the packets to the neighbor closest to the destination among all its neighbor, as illustrated in fig 2. Greedy forwarding can be very efficient in the sense that it makes the largest progress at each step.

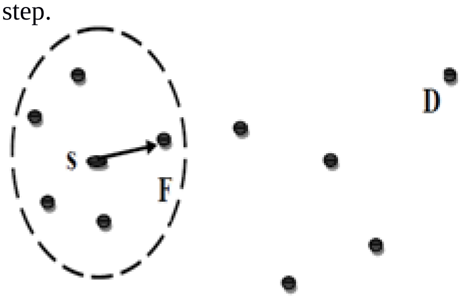


Fig.2 Greedy forwarding: node F is the one of the closest to the destination D among all its neighbor of S.

However, it would fail when reaching a dead-end, i.e., a node that has no neighbors closer to the destination. To resolve the dead-end problem some associated recovery mechanisms have been proposed [6], [10]. One of these mechanisms is face routing (perimeter routing), which guarantees that the packet can reach the destination if a path exists.

(e) Distributed Cooperative Geographic Routing

Consider a cooperative sensor network, where the nodes are grouped into coalitions. Suppose a sensor node S would like to route data to a destination node D. As in traditional geographic routing, we assume that each CH knows its geographic location by using some localization technologies such as GPS. Its also knows the locations of all the member nodes within coalition, those of the CHs in its neighbor coalitions and that of the destination. Moreover, it also has knowledge of the number of nodes within each within each neighbor coalition.

In general, a CH would forward the data to the coalition with minimum energy cost among all its neighboring coalitions, Particularly, based on the location information, CHi computes the energy Cik and CkD by (5) for all k ε Ui is the set of i's neighbor coalition that have not yet received the data yet, and forwards the data to CHk* such that

k* = arg min[Cik + CkD] (7) k Є Ui 7)

The protocol continues stages by stages until the coalition that contains destination node receives the packet.

Algorithm for Cooperative Geographic Routing is summarized as

1. For a given source S and destination D pair, let S send the routing packet to its coalition head CH1.
2. CH1 broadcasts the packets to all nodes within the coalition.
3. Choose k* as the next stage coalition, with
   k* = arg min[Cik + CkD]
   k Є Ui
4. Let CHk* broadcast training symbols.
5. Based on the training results, each node independently adjusts its transmission power according to formula (4).
6. All nodes in this coalition cooperatively transmit the data packets to CHk*.
7. Repeat step 2 to step 6 until CHD receives the packet.
8. CHD sends the packet to the destination node D.

In the above, we assume a dense sensor network where CHi can always find neighbor coalition to forward a packet to. Hence dead-end problem is out of scope.

5. Optimal Cooperative Geographic Routing

(a) Optimal Coalition Size

Consider a sensor network, where each node has a strict power constraint Pmax. Data need to be routed from a source node S to a destination node D. In each transmission, an intermediate node would multicast the packet to a subset of its neighbors, and ask the nodes in the subset to dynamically form a coalition and cooperatively transmit the packet to next stage destination (point-to-multiple-point transmission first and then multiple-point-to-point transmission). Note that the node can participate in the cooperative transmission are restricted to the intermediate's one-hop neighbors.

During the routing process, the number of neighboring nodes that participate in the cooperative transmission, i.e., the size of the dynamic coalition plays a key role. Here the energy cost of each transmission is the sum of the multicast cost and the cooperative cost. Intuitively, a larger coalition would reduce the cooperative cost, but may require more multicast energy to reach nodes further away, whereas a smaller coalition would require less multicast energy but higher cooperative cost. Thus motivated, we characterize the optimal coalition size to minimize the transmission cost in the following.

Consider a transmission from node a to node b, node a would multicast the packet to a subset of its neighbors and ask the node in this subset to cooperatively transmit the packet to node b. Let na denote the number of a's neighbors and ka denotes the number of participating neighbors, where Ka = 0,1,2, …, na. Then the total cost is given by

$$C_{ab} = \min_{k_a}[P^M_{k_a} + P^C_{k_a}] \qquad (1)$$

where $P^M_{k_a}$ is the multicast cost to reach k_a neighbors and $P^C_{k_a}$ is the cooperative cost from the k_a +1 (plus node a itself) node to node b, with

$$P^M_{k_a} = \max \{ P_{a1\_direct}, P_{a2\_direct}, \dots P_{ak_{a}\_direct} \}, \qquad (2)$$

Where P_{ai_direct} is the cost of point-to-point transmission from node a to node i. The cooperative transmission cost $P^C_{k_a}$ can be obtained by solving the following optimization

$$\min_{P} \; P^C_{k_a} = P_a + \sum_j^{k_a} P_j$$

$$\text{such that } P \leq P_{max} , \frac{1}{N}\left(\sum_{j=1}^{k_a} \sqrt{P_j/d^{\beta}_{jb}} + \sqrt{P_a/d^{\beta}_{ab}}\right)^2 \geq \Upsilon, \quad (3)$$

where $P = [P_a , P_1 , P_2 \dots P_{ka}]^T$, d_{ab} is the distance from a to b, β is the path loss exponent, and N is the Gaussian noise. The second constraint indicates the SNR requirement at the receiving node is 1.

Let $P^{opt} = \left[P^{opt}_a , P^{opt}_1 , P^{opt}_2 \dots P^{opt}_{ka}\right]^T$ denotes the optimal solution. Then, the total energy cost for the cooperative transmission is given by

$$P^C_{k_a} = \sum_{j=1}^{k_a} P^{opt}_j + P^{opt}_a \qquad (4)$$

Note that $k_a = 0$ indicates point-to-point transmission from a to b, with $P^M_0 = 0$ and $P^C_0 = P_{ab\text{-}direct}$. Since k_a is discrete and bounded,one can use exhaustive search to find the optimal k_a that minimize C_{ab}.

Therefore, the original network can be modeled as edge-weighted graph G= (V, E,C) , where V is the set of vertices, E is the set of edges, and C = { C(e) , every e Є E } is the set of cost on each edge.

(b) Minimum Energy Cooperative Routing

The minimum energy cooperative routing problem (MECR) can be defined as follows.

Definition 4.1: (MECR) The Instance is given by an edge-weighted directed graph G= (V, E, C) and a source-destination pair S-D. Let p be a path in G and C(p) be the sum of the costs over the edge on p,

$$C(p) = \sum_{e \in p} C(e)$$

The problem is to find the optimal path p0 such that C(p0) is minimized. The routing problem formulated above is a shortest path routing problem on the new directed graph and can be solved by the well-known Dijkstra's algorithm. Compared to cooperative geographic routing, the minimum energy cooperative routing would achieve better energy saving, because of following reasons.

1) It exploits optimal power allocation within each coalition to reduce the cooperative transmission cost.
2) It characterizes the optimal coalition size to minimize the energy cost of each transmission whereas in cooperative geographic routing, the coalition size is predetermined.
3) It chooses the routing path based on global information, whereas in cooperative geographic routing, only local information is available.

According to [13], Every node in the network is either a member node of some cluster or cluster head. It is assume that dense sensor network where CHi can always find a neighbor coalition to forward a packet. So, dead-end problem is out of scope.

Consider SNR requirement Ɣ is normalized to 1 and all nodes in the cluster are within the transmission range.

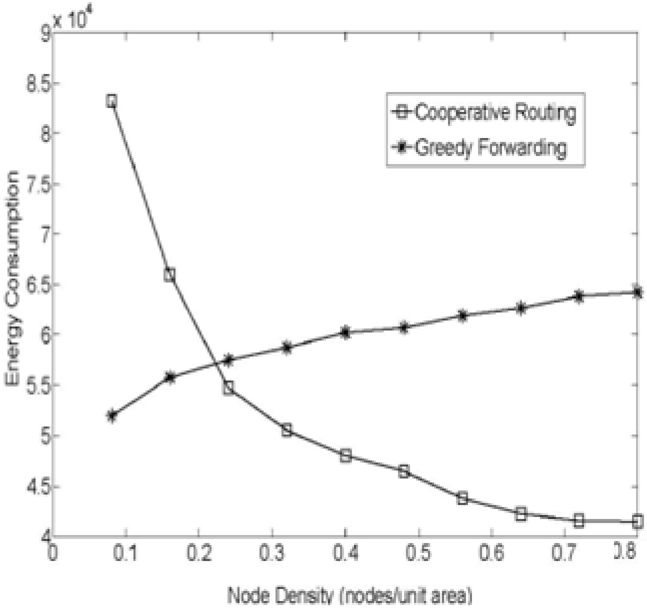


Fig 5.1 A comparison of energy consumption

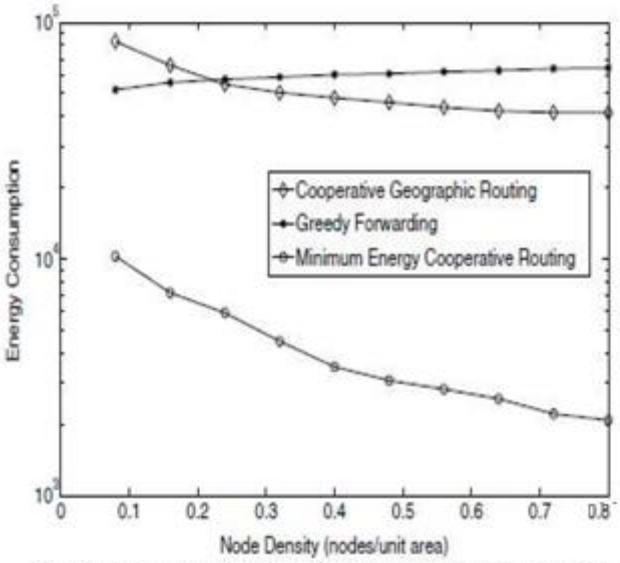


Fig 5.2 Energy consumption of minimum cooperative routing

As seen in Fig 5.1, when the node density is small, cooperative geographic routing is not as energy efficient as greedy forwarding. This is because the number of nodes within each coalition is quite small and there is virtually no node cooperation gain. However, when the node density is moderate or high, cooperative geographic routing out performs greedy forwarding and yields significant energy.

As seen in the Fig 5.2, minimum cooperative routing consumes less energy as compare to greedy forwarding and cooperative geographic routing. This is because an optimal coalition size that minimizes the energy cost of each transmission where as in cooperative geographic routing the coalition size is pre-determined, only local information is available.

6. Conclusion

The paper begins with a brief introduction to wireless sensor networks. Then we discussed the properties and challenges in wireless sensor networks and also some of its applications. Later a brief idea about different types of routing protocol has been given.

Finally we done the comprehensive study of the cooperative geographic routing and minimum energy cooperative routing. We have seen the tradeoff between the multicast cost and cooperative transmission cost, and characterized the optimal coalition size that minimized the transmission cost. Minimum energy cooperative routing would achieve better energy saving.

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