A survey on routing in wireless sensor networks

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Accepted on August 10, 2006

Abstract One of the most important issues in wireless sensor networks is data delivery service between sensors and the data collection unit (called *sink*). Although sensor networks and mobile ad hoc networks are similar to some extent, they are radically distinct in many aspects. Sensor networks have many unique features, making them more challenging and need further research efforts. The existing routing protocols for sensor networks can be classified as indicator-based and indicator-free. In this survey, we make a comparative study of these protocols. Open issues and research directions are pointed out as guidelines for our future work.

Keywords: sensor network, distributed system, routing, ad-hoc network.

Sensor technology has been developed for many years[1]. Recent advances in electronics have made the traditional sensor smaller and cheaper. Equipped with processing and communication capabilities, sensors nowadays can cooperate with each other. Sensors deployed in an application field self-organize and form a virtual organization called wireless sensor networks (WSNs).

A variety of exciting applications can be implemented on top of WSNs[2]. Example application areas include environmental and habitat monitoring, health care, and security surveillance[2—5]. NASA maintains a sensor web in Antarctica in New Mexico Desert[6] to monitor the air and soil temperature and humidity in real-time[7]. The University of Southampton' s Envisense Center hosts many environmental observation and forecasting systems. The FloodNet[8] project provides information about the coastal erosion around some small islands. Wind farms are intended to be built there. GlaceWeb[9], another project initialed by the Envisense center, is to monitor the glacial status to obtain valuable information about the global warming and climate changing.

Sensor nodes are usually randomly deployed in a sensing field. Some types of information are generated by sensors and the information must be delivered to one or a set of designated gateway units (call sink) as depicted in Fig. 1. Usually, the sink has reliable connections (e.g. wired or satellite) to the Internet, powerful processing capabilities, and enough power supplies (e.g. wired). Sensor nodes are mainly composed of four basic components: a sensing module, a processing module, a transceiver, and a power supply. There could be some other modules such as a location determining system[10, 11], a power generator, and a mobilizer. Although a sensor network is similar to some networks to some extent, unique characteristics as follows make problems in sensor networks significantly different from that of others:

(1) Power issue is the most important concern[3,4,12—14]. Sensors are usually self-powered by batteries. The total energy of a sensor is on the order of 1 joule[4]. Some may have solar cells which can scavenge energy for around 1 joule per day outdoors, and 1 mille joule indoors. Since it is often impractical to recharge a depleted battery, energy-aware protocols are desired. Among all the components, the transceiver for transmissions and receptions accounts for the major portion of the power usage[15]. A power efficient routing protocol can significantly enhance the connectivity and elongate the lifetime of the network.

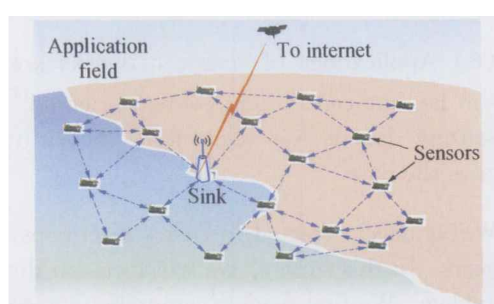

Fig. 1. A paradigm of routing in WSNs.

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(2) Resources for processing, storage and transmissions are extremely limited. Due to the cost, sensors are made of simple circuits. The Berkley MICA series Motes[16] have 8 MHz processors, 128 K programmable memory, 4 K RAM and 512 K flash memory for storage. The packet is fixed 36 bytes on 19.2 Kbps channels. As the transmission range is around 10 meters in outdoor environments, it makes less sense that all sensors have direct connections to the sink. Alternatively, multi-hop routing is more likely to be applied. Of these, sensors do not only function as a data generator, but serve as a router to relay messages.

(3) Global ID or unique address is not always available[3]. According to the nature of massive deployment and production, a globally unique ID needs long bits. However, packets for WSNs are dozens of bytes long. In TinyOS[17, 18], all packets are fixed 36 bytes. For the ZigBee design, given a 64 bit unique ID, nodes are preferred to employ a 16 bits local ID assigned by users or applications.

(4) The positions of individual sensors do not need to be predetermined[3]. WSNs are allowed to be randomly deployed to the terrains, e.g. dropped from an airplane[19]; the application field could be hostile, which is inaccessible to human (e.g. in forest fire detection and chemical pollution monitoring applications); and sensors are prone to failure. To efficiently operate a sensor network, the management and topology control mechanism must be flexible and robust[20]. Protocols must be fault-tolerant.

(5) Sensor nodes are large-numbered and densely deployed in a field. The density can be defined as the average number of neighbors[3] that a sensor can directly communicate. Algorithms should be scalable and self-organized for the huge number of nodes.

(6) Applications of sensor networks are more likely to be data-centric and content-oriented[21—24]. The sensing data is less relevant to the entity that generates the data.

WSNs have attracted intensive attentions in recent years. In this survey, we will focus on the routing problem. We first made a comprehensive comparison between WSNs and MANETs for their similarities and differences, then present the existing techniques, and finally, we point out some existing problems and future research directions.

1 Similarities and differences between WSNs and MANETs

Although Mobile Ad-hoc NETworks (MANETs) and Wireless Sensor Networks (WSNs) share some common features, they are different in many aspects. In this section, we compare WSNs and MANETs for their similarities and differences.

1.1 Similarities

MANETs are characterized by multiple entities, frequently changing network topology and the need for efficient dynamic routing protocols. WSNs are featured by tiny devices with extremely constraint resources, high density deployment and multi-hop wireless connections.

WSNs and MANETs are similar in the following aspects:

(1) Ad-hoc mode: no fixed infrastructure or bases station is need. Entities communicate with each other by multiple wireless links. Each node serves as a router to forward packets for others.

(2) Resource constraint devices: nodes are resource constraint. Devices of MANETS are typically hand-held devices with lower power capacities. Sensors are even smaller.

(3) Power issue: nodes are usually powered by batteries (chargeable or none-chargeable). Power-aware and energy-efficient algorithms can significantly improve the performance of system.

(4) Wireless communications: The underlying links of MANETs and WSNs are both the wireless channels.

1.2 Differences

Despite the certain salient common characteristics, there are several critical differences between the two networks:

(1) Resources: Although both of MANETs and WSNs are resource constraint computing environments, the critical level are different. MANETs are just lack of capability. For current popular hand-held devices, processors are typically hundreds of MHz, memory is order of dozens of Mega-Byte and

rechargeable batteries can last several hours. Storage spaces are pretty large so that complex statistics can be stored locally. WSNs are composed of devices with extremely critical resources. A typical sensor, for example Berkeley Mica2[25], is equipped with a 8-bit RISC processor, 128K programmable memory, 4K SRAM and 512K flash storage space.

(2) ID mechanism: Entities on MANETs always have a globally unique ID (e.g. MAC address or IP address). Routing information can be organized based on this ID. In WSNs, ID is not always available and distinguishing neighbors becomes an issue.

(3) Communication pattern: Nodes in MANETs are peers. There are no priorities such that some one is more important than the others. Transmission could occur between any pair of nodes. Depletion energy of a single entity is unacceptable—no one likes to fail at the very first time. "Hot spot problem" must be prevented. In addition, like in the Internet, multicast and globally broadcast is not so frequent. Transmissions on MANETs are address-centric. On the contrary, in WSNs, the sink accounts for the most important role serving as the only gateway between network and users. The sink is always one opposite of transmissions. WSNs do not have a peer-to-peer mode[26,27] but a master-slave mode. None-sink to none-sink communication is very rare, but the multicast and broadcast transmissions are so common that their effects cannot be ignored. On the other hand, failure of individual nodes can be ignored unless it is the sink.

(4) First metric to evaluate the performance: In MANETs, QoS and Bandwidth usage are the most concern and first criteria[28], and the power consumption is of the second importance as the energy source can be replaced or recharged. WSNs consist of unattended devices. The task of optimizing the routing is to lower down the power usage to optimize the network availability.

(5) The first challenge: As the nodes in MANETS have great abilities to move, mobility becomes the most challenge[29]. Connections are up and down in an arbitrary fashion and topology of network keeps changing, making the discovered route prone to failure. In WSNs, although both the sink and the data source could move[30], sensors are always lack of mobility and usually stationery. The failure of sensors is the dominate factor for topology changing[31].

(6) Density: Here, the density is defined as the average number of neighbors per node[3,32]. The density μ can be roughly calculated by: $\mu(R) = (N\pi R^2)/A$ with unit disk communication model, where N is the number of sensors in an area A, and R is the radio transmission range. In MANETs, nodes are sparsely scattered, and in WSNs they are high density deployed. Different levels of density lead to different solutions to achieve reliability of data delivery. In MANETs, the lower data-link layer helps to ensure the reliability of one-hop transmissions. Single path is sufficient for end-to-end communications. In WSNs, sensors are prone to failure, and local channels are broadcast without an acknowledge mechanism. The one-hop transmission can be very unreliable. Under such situations, the transmission qualities are always achieved by multi-path routings[33,34].

(7) Wireless multicast advantage (WMA): Different from the traditional networks, the so-called wireless multicast advantage (WMA)[13] property is held in WSNs. With WMA, when transmitting, all directed neighbors of the transmitter can receive the packet for free. It exploits the broadcast nature of wireless medium, and allows the sender to reach multiple nodes simultaneously without penalty. Receivers outside the transmission range will not get enough signals which are sufficient to achieve the required Signal-to-Noise (SNR) threshold. They just ignore the signal as noise. However, in MANETs, transmissions are address-centric without WMA.

(8) Protocol design: Inherited from the traditional wired network, the layer concept is still valid in MANET design, and protocols are modulated developed layer by layer. On the contrary, WSNs is on the top of embedded systems. The all-in-one design is deeply preferred.

2 Routing protocols in WSNs

Routing in WSNs has attracted much attention. In general, it can be divided into indicator-based and indicator-free algorithms. In the indicator-based algorithm, there is always an initialization phase where a designated policy is applied. Accordingly, all nodes generate own indicators to help determine the routes. In the indicator-free algorithms, routes are built on-demand. Note that some hybrid approaches combine two factors.

2.1 Indicator-based approaches

In this category (Fig. 2), some indicators were built for each sensor in the setup stage. Sensors then follow those indicators to make decisions when routing. According to different types of the indicator, we further category this kind of protocols into several sub-classes: geography based, gradient based and cluster-based protocols.

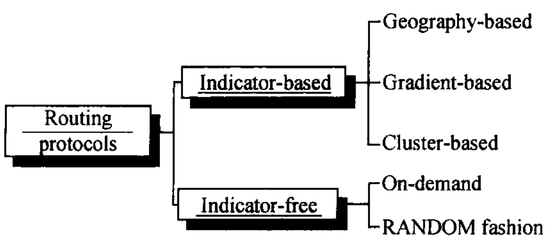

Fig. 2. A taxonomy of routing protocols in WSNs.

2.1.1 Geography based protocol

Some protocols assume that precise location information of sensors is available. Routes are established by the locations of the data source and the destination.

LAR[35] is a geography-based protocol which is originally designed for MANETs. Instead of flooding the whole network, LAR selected a small region, the "request zone" to flood. In Ref. [35], two shapes of request zone were proposed and evaluated. One was a rectangle bounded by the source and destination. And the other shape was a sector whose center was located at the destination and the radius is the distance from the source to the destination. DREAM[36] has a similar idea. The flooding region was also a sector-like shape, but the center was located at the source instead of the destination. These two approaches were published in the same year.

Greedy perimeter stateless routing (GPSR)[37] is a single path algorithm which does not need flood at all. GPSR consisted of two methods to determine a route: greedy forwarding when it was possible to employ; and perimeter forwarding when greedy forwarding failed. In GPSR, packets hold the source and destination locations. Normally, packets were in the greedy mode. When receiving a packet in the greedy mode, the forwarder selected the neighbor who was geometrically closest to the destination as the next hop. Accordingly, the destination was greedily closed hop by hop until it was reached. Potentially, an intermediate node encountered voids—all the directed neighbors are farther to the destination than itself. Then the packet was transferred to the perimeter mode to route beyond the void (Fig. 3). GPSR applied the right-hand rule to traverse a void. A perimeter mode packet was marked with the location of the node from which the packet entered the perimeter mode. It went farther than the current forwarding node to traverse the perimeter of a void. Right-hand rule was followed till the packet arrived at a node that was closer to the destination than the node which made the packet enter the perimeter mode.

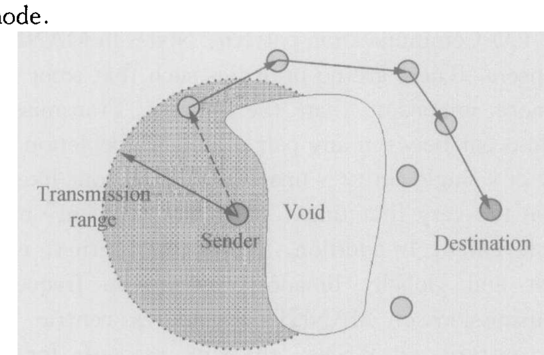

Fig. 3. The void of forwarder and the right-hand rule to walk around it.

Geographical and energy aware routing (GEAR)[38] was motivated to solve the problem of void. GEAR borrowed the idea from traditional distance vector routing algorithms developed for many years. When a packet came for forwarding, each forwarder built an entry, called learned cost H, as the estimated transmission cost to the destination. Initially, it is the physical distance from the node to the destination. It could be updated according to the following operations. Consider a scenario of which node M wants to send a packet to R as shown in Fig. 4. Suppose M selects N as the next hop. Let $H(N,R)$ denote the learned cost of N to R. H is then initialized to be 2. Black points represent failure nodes and they are voids for N. N finds and forwards the packet to its neighbor O who has the least H value. Note that currently O has the H value $H(O,R) = \text{Distance}(O,R) = \sqrt{5}$. N updates its own learned cost

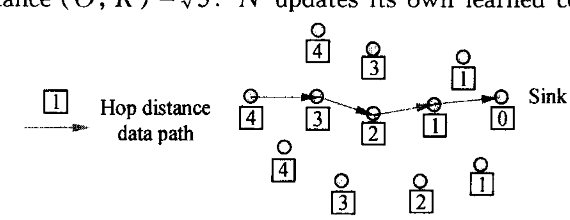

Fig. 4. An example of gradient-based routing.

$H(N, R) = H(O, R) + \mathrm{cost}(O, N)$ as the new estimated cost of N. From now on M directly sends packets to O instead of N since O has less H value than N. By this feedback mechanism, learned cost can be calibrated closer and closer to the real value.

Fang et al. in BOUNDHOLE[39] gave a more restrict definition of a void. With the proved TENT rule, all voids can be predetermined. Once all potential voids are pre-computed, they are stored locally. With the right-hand rule, the strategies to route across those voids are pre-calculated and stored locally for future transmissions.

Two-tier data dissemination[30] (TTDD) is to support multiple mobile sinks. Each data source (assume they are static) in TTDD proactively builds a virtual grid structure. Grid is a $\alpha \times \alpha$ square. Source itself is in the origin of the grid. Nodes at the crossing point locations (or the nearest node to that position) serve as the router to forward data. Within the grid that sinks fall, data are transmitted through flooding called lower-tier transmission; in the higher-tier, data are forwarded between crossing point nodes. TTDD is independent on low layer geography routing algorithms. It does not care about how data are delivered between crossing points through multi-hop. Neither does it show how the routes are found at the route setup stage.

There are also some other geography-based approaches which share the similar idea, for example, SPAN, GHT and so on.

Geography-based approach is a promising routing scheme with good scalability of needing less control states in both the packet header and the nodes. The route is guaranteed when it exists; when the destination does not exist, the algorithm terminates at the node closest to the destination. It also provides omni-direction data delivery services by which messages can be sent between any pair of nodes. However, all these approaches need geography information—they are too expensive for simple sensors.

2.1.2 Gradient-based protocol

Instead of employing the absolute geometric distance, another kind of solutions utilize the relative distance between nodes. Such relative distance is the "gradient" corresponding to a particular originator. Some approaches select the sink as the originator, for example, MCFN[40], GRAB[34], ARRIVE[41], and GRAd[41]; and others utilize the data source as the origin, for example, Direct Diffusion[33,42].

MCFN[40] studied the problem of delivering message from sensors to the sink. In MCFN, each node maintained a cost field as the minimum cost from that node to the sink. In practice, this cost was actually that of the reverse direction—from the sink to sensors. Under the assumption that links were symmetric, these two were identical. Once the cost field was established, messages flowed to the sink along the optimal path.

As exemplified in Fig. 4, the hop number is employed as the cost field. Note that energy is also a choice for the type of the cost field. The main contribution of MCFN is that it presents a scheme to avoid the excessive advertisement messages when establishing the cost field. It makes sure that every node only advertises its cost field once with the correct value. GRAB[34] was a mesh version of MFCN to increase the reliability. In GRAB, rather than using the single optimal path, a mesh between the source and the sink was formed, and all the nodes in that mesh were involved. The width of the mesh was designated and proportional to the distance to the sink. To build the mesh, the concept of extra credit was introduced as the budget that messages could consume. GRAB greatly increased the reliability of MCFN without introducing too much overhead—only the packet header was a little bit longer. The most promising property of MCFN and GRAB is that forwarding or not was decided by the receiver but not the sender. Thus, no location or node ID is needed.

ARRIVE[41] applies the hop number as the gradient. Different from GRAB, nodes in ARRIVE explicitly maintain the list of directed neighbors and assign the next hop. The main contribution of ARRIVE is the introduced random factor to increase the reliability instead of the deterministic one employed in GRAB.

Different from the above destination-based gradient setup, Direct diffusion[42] and its multi-path version[33] established the gradient originated from the data source but not the sink. Firstly, the sink floods a query. In the flooding, every node records from which it receives the query. By this means, reverse paths back to the sink are established. The data source node then follows these reverse paths to the sink. In the process of reply, intermediate node record again from which neighbor it receives the first data. After the data successfully arrives at the sink, sink then reinforces the best path from which the data comes first. The sink just needs to acknowledge one of its neighbors: you are on the optimal path. That neighbor then forwards this announcement to the neighbor from whom it gets the very first data. This propagation of announcement never stops until it arrives at the data source. In Ref. [33], a braided version of directed diffusion is proposed. The alternative path does not have too bad performances than the optimal one.

There are also some other kinds of gradient-based protocols such as the ARRIVE[41] and GREENWIS[43].

Gradient-based approaches do not need location information, but need symmetric links. They are scalable with optimal paths. However, they can provide a little portion of data delivery services—only for the transmissions from others to the gradient zero.

2.1.3 Cluster-based protocol

Another kind of routing protocols is cluster-based solutions. Some virtual clusters are formed and the cluster-heads are selected. Sensors send the packet to a cluster-head and the cluster-heads then take the responsibility to forward the packet to the sink.

The cluster-head gateway switch routing[44] (CGSR) selected the cluster-head by least ID or the highest connectivity. A cluster contains a cluster-head and all its direct neighbors. Any two adjacent cluster-heads have at most 2 hops away in between. Nodes between two heads belong to both clusters, and serve as the gateway to do the inter-cluster transmissions. None-head nodes communicate with any other through their cluster-heads. The underlying inter-cluster routing utilizes the DSDV[45] which is a table-based wireless routing protocol.

Low energy adaptive clustering hierarchy (LEACH)[46] has a distributed cluster formation scheme. LEACH assumed that all nodes have directed connections to the sink. According to the requirement of the application, sensors have a fixed probability to be a cluster-head. After being deployed to the sensing field, sensors independently determine whether it serves as a cluster-head or not. Cluster-heads then broadcast an announcement to others. After receiving the announcements, the none-head nodes selects the closest one as its head and joins its cluster. When having data to be transmitted, nodes send it to the cluster-head first. Cluster-head then forwards it to the sink. There are no inter-cluster operations, and all cluster-heads directly communicate with the sink. The shape of clusters in LEACH is like a Voronoi Diagram[47]. An example is depicted in Fig. 5. Clusters are bounded by a perpendicular bisector between cluster-heads. LEACH also proposed a rotation scheme that the members of a cluster serve as the cluster-head in turn.

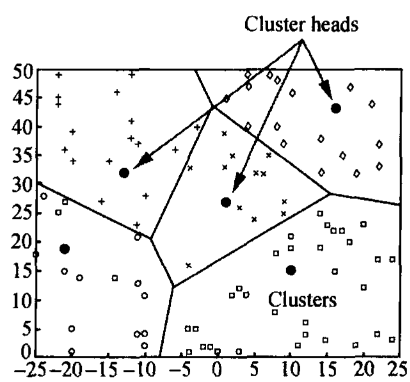

Fig. 5. Clusters in LEACH.

There are also some other cluster-based protocols, for example, geographic adaptive fidelity[48] (GAF), cluster-head gateway switch routing[44], CLTC[49], and DIMENSION[21,50−52].

Cluster-based protocols are always independent of the underlying routing algorithms. However, they need extra communication to maintain the cluster architecture.

2.2 Indicator-free approaches

Indicator-free algorithms have no initialization phases and the packets are transmitted by on-demand or random fashion.

2.2.1 The on-demand fashion

In this fashion, route requests are sent out to find a route; the reply message contains the route information.

Ad-hoc on-demand distance vector routing (AODV)[53] was an improved algorithm of DSDV[45]. When a source desired to send a message, it initiated a path discovery process to find the route. The route request packet (REQ) was flooded to the network. In order to establish reverse paths back to the source, intermediate nodes recorded from which neighbor it got the REQ first. When the REQ arrived at the destination, it then sent back a route reply (REP) to the source following those reverse paths. AODV needs the assumption that links are symmetric, otherwise the REP may not be able to arrive at the source and AODV would fail.

Dynamic source routing (DSR)[54] is an improved algorithm of AODV with the least assumptions on wireless communications.

On-demand fashions are always robust and reliable. However, usually they need too much effort on finding a route.

2.2.2 The random fashion

To meet some optimal criteria, algorithms in this fashion introduce some random factors when determining the route.

Rumor routing[55] is an algorithm intending to avoid flooding. In the rumor routing, an agent was employed to let a subset but not all nodes know an event. The agent was a special packet carrying information of the corresponding event and randomly traveling the network with a certain lifetime (TTL). It informed all the passing by nodes of the event such that these nodes became the witness of the event. These witness nodes then were able to build reverse paths towards the event. When querying, the sink sent out some agents to scout a witness of the event. Note that the interaction between an agent and a witness is of dual-direction. If a node that an agent passed through was already a witness of some other events, the agent then absorbed those events recorded in the node too. So the farther an agent moved, the more information it contained until it died. The novel point of Ref. [55] is, although the agent randomly traversed the network, an algorithm that tried to make the travel path as straight as possible (but not guaranteed). However, rumor routing does not ensure successful rate of finding a route in any sense. Neither is the path optimal.

There are also some other random fashion routing approaches, such as energy-aware routing[56] and ReINForm[57].

Random fashion approaches are always lack of stability of routing.

3 Conclusions and future research directions

In this section, we will conclude the previous work and point out some existing problems. We will then propose the corresponding preliminary solutions. We would like to sketch the direction of future work.

In this paper, we present a comprehensive survey on current routing techniques in wireless sensor networks. We discuss the communication patterns which are the routing services provided, and classify those approaches into two major categories. After that, we provide the metrics to evaluate the protocols and according to that, we give a comprehensive comparison between them. Finally, we highlight most challenges and point out the future research directions.

The existing routing protocols provide some levels of desired data delivering services, but all of them have their own drawbacks. Geography-based protocols are scalable solutions. They have relatively low system overhead and can be employed for most of the communication patterns. Some multi-path versions showed encouraged reliability and fault-tolerant capabilities. However, the assumption of precise location information significantly limits the application range. Gradient-based protocols eliminate the need for location information. The performances on overhead and reliability are attractive. However, they can only be employed in some particular scenarios. Cluster-based routings always need extra control messages to maintain the structure of the cluster. And how to efficiently form the cluster, how to assign the cluster head and how to efficiently transmit messages intercluster are all challenging jobs. On-demand routing requires both the sensor and packets to reserve enough spaces to contain routing control information. Although random fashion routing shows great development potential, a gigantic packet header and node header should be decreased before it can be employed in practice.

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