Strategies for Resource Management in Wireless Sensor Networks

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Abstract: Along with the emergence of Wireless Sensor Network (WSN) applications, energy efficiency, Quality-of-Service (QoS) and scalability are becoming key design challenges. In our former work, various clustering and routing algorithms have been proposed as management strategies for WSNs. In this paper, we classify WSNs according to their properties of deployment, and summarize our management strategies to address the characteristics of each class. We mainly focus on the clustering and routing algorithms, where various kinds of context information are utilized as design parameters to achieve optimal performance.

1 Introduction

Wireless Sensor Networks (WSNs) are composed of sensor nodes, which measure physical parameters in terrains of interest, such as temperature, humidity, presence of objects etc., and send gathered data to a data sink where information is processed. As sensor nodes are left unattended after deployment, sensor nodes are usually battery powered. Therefore, energy remains one of the critical resources of WSNs. One of the main components of energy consumption is wireless communication that is usually carried out by on-board radio transceivers. During radio signal propagation, the transmission power decreases proportionally to the square of distance or worse. For nodes with limited transmission power, transmission range as well as bandwidth is also highly constrained in WSNs. Recent advances of electronic technology yield small and inexpensive sensor nodes [PK00], and motivate development of large-scale networks. Therefore, scalability is becoming another major design attribute of WSNs.

Since radio communication among sensor nodes is the main drain of energy in WSNs, reducing the amount of radio transmission becomes the goal of our resource management. Clustering and routing algorithms are two major research fields to address the objectives (e.g. prolonging the lifetime of WSNs, achieving scalability for large-scale networks, etc.) of our management strategies. The objective is the efficient use of resources (e.g. battery power, bandwidth, etc.) in WSNs.

2 Strategies of Resource Management

Management of WSNs can be either centralized or distributed. In a centralized WSN, nodes are connected hierarchically with the data sink as the root of the structure [YMK02] [YLMT08]. In contrast, networks of large physical dimension tend to be distributed, meaning that nodes are organized locally and communicate with each other using multi-hop routing. [XHE01] [YLST09].

By organizing nodes into small groups, clustering techniques aid effectively to the energy-efficiency and scalability of large-scale WSNs. A generic cluster has a cluster head and several cluster members. Sensor nodes transmit data only to the local cluster heads which aggregate received data and route them to data sink. Aggregated data is routed to data sink through an overlay of cluster heads [YS04], while releasing the cluster members from the global routing tasks.

In centralized networks, routing paths are established statically using specific network structures. In [YMK02] and [YLMT08], a WSN is structured as a spanning tree joint by cluster heads, with the data sink at its root. In distributed networks, routing paths are built dynamically using the local knowledge of nodes [YLT09] [YLHST09] [YLRT09]. For delay sensitive WSN applications that require real-time services, time for a detected event to arrive at data sink is of significant importance. In WSNs, efficient routing paths between sensor nodes and data sink can help to achieve both energy-conservation and high QoS.

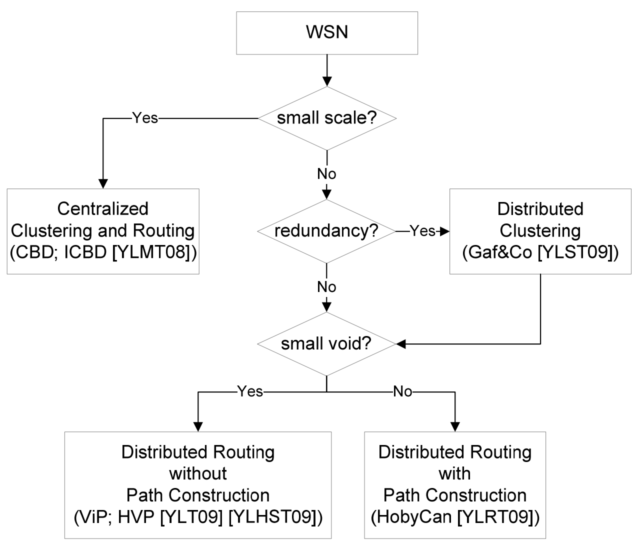

Figure 1: Classification of WSNs and management strategies

In [YLMT08] [YLT09] [YLHST09] [YLRT09] [YLST09], we have proposed various clustering and routing algorithms as management strategies for WSNs. In this paper, we categorize WSNs according to their properties, and apply our algorithms to suit each class. The taxonomy of our strategies is illustrated in Figure 1. Our algorithms tightly involve context information as important parameters. For instance, the battery status of sensors is one of the essential considerations during clustering and routing processes. As WSNs are deployed to various environments, context information regarding the terrain can influence the performance of WSNs. The existence of deployment voids, for example, is also considered as an important parameter of designing the clustering and routing algorithms.

2.1 Strategies in centralized WSNs

Small-scale WSNs are usually organized in a centralized manner, where nodes are connected in a static structure to the data sink. We proposed the Clustering with Dynamic Budget (CDB) algorithm and the Interactive Clustering with Dynamic Budget (ICDB) algorithm [YLMT08] to generate spanning tree structures (Figure 2(a)) in WSNs, where hierarchical routing from nodes to data sink can be applied. Both clustering algorithms do not only target energy conservation and scalability of WSNs, but also efficient routing between sensor nodes and data sink. CDB and ICDB initiate a clustering process from the data sink, and recruit nodes in the growing tree structure.

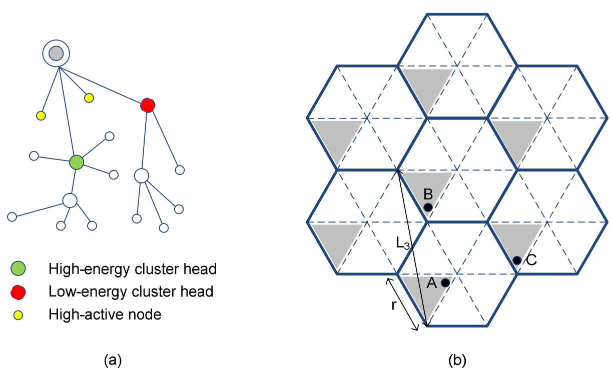

Figure 2: Classification of WSNs and clustering strategies. (a). Centralized hierarchical clustering (CDB; ICDB). (b). Distributed geographic clustering (GAF&Co).

Careful selection of cluster heads and optimal formation of clusters help to improve the end-to-end delay of packets. Clusters with bounded sizes contribute dramatically to the efficient task allocation and energy balance within WSNs [KD06]. A way to form bounded clusters is to constrain cluster sizes with a predefined budget value. In such budget-based clustering algorithms, cluster heads are assigned budget values that indicate the maximum number of their cluster members. Sensor nodes in a network typically have different remaining energy or activities, which contributes to the complexity of the network. Our algorithms utilize such context information in estimation of dynamic budget values, election of cluster heads, as well as selection of cluster members. In CDB, cluster heads with more remaining energy are assigned bigger budget values to improve load balancing. Sensor nodes with higher activity rates are placed nearer (in terms of hops in a spanning tree) to data sink, so fewer hops will be needed for frequent messages coming from the active nodes. As an extension to CDB, ICDB employs activity rates of cluster members as feedback to further optimize the size of the clusters.

2.2 Strategies in distributed WSNs

Large-scale WSNs tend to be organized in a distributed manner, where nodes are locally self-organized. Routing via multiple hops is the major source of energy consumption in distributed WSNs, which also affects significantly QoS of the network application. Among various routing algorithms, single-path geographic routing with Greedy Forwarding (GF) is attractive for WSNs [AY05]. In a basic GF algorithm, a node communicates only with its direct neighbors (1-hop). The neighboring node that further minimizes the remaining distance of a packet to its destination is selected as the next hop. Such localized routing approach is effective and accommodates dynamically to changes, which only requires position information of sensor nodes.

However, voids in the deployment or node failure can cause routing holes [AKJ05] in the network, which often cause traditional geographic routing algorithms to fail. This is basically caused by the local minimum phenomenon illustrated in Figure 3(a). When using GF, packets get stuck at node *A* since there is no neighbor node closer to the destination than node *A* itself. In this section, we summarize our strategies addressing the local minimum problem from different perspectives. In dense networks, distributed clustering algorithm GAF&Co [YLST09] is used to conserve energy by switching off redundant nodes. For carefully deployed networks, simple variants of GF (VIP; HVP [YLT09] [YLHST09]) are introduced to bypass small routing holes while keeping overhead low. For networks with large voids, dedicated detour paths are constructed with routing algorithm HobyCan [YLRT09] around routing holes.

Distributed geographic clustering (GAF&Co): As more and more sensor nodes are employed in modern WSNs, redundancy of sensor nodes can be utilized to conserve energy. Some clustering algorithms [XHE01] [SKRT07] divide a geographical region into a number of smaller zones, namely clusters. Nodes are classified into clusters according to their geographic properties. In each cluster, only one representative node is active, while the redundant nodes operate in energy-saving mode to prolong network lifetime. Routing activities are carried out only by the representative nodes, namely the cluster heads.

It is observed that the connectivity of a network is reduced by such clustering algorithms, where only a subset of nodes is involved in global routing. When applying a generic geographic routing algorithm, it is more likely to encounter the routing hole problem as only a subset of nodes is active.

We presented a novel clustering algorithm called GAF with COnnectivity-awareness (GAF&Co) to prevent routing holes introduced by switching off nodes. The proposed algorithm divides a network into hierarchical hexagonal cells, as in Figure 2(b). Each hexagonal cell has 6 triangular sub-cells. One set of the sub-cells with the same relative position in the hexagonal cells are set to be the active sub-cells, where one sensor node of each sub-cell is kept active for routing activities. The rest of sensor nodes are switched to energy-saving mode.

The main objective of GAF&Co is to avoid routing holes caused by existing clustering strategies. As in Figure 3(b), the maximal angle formed by points in an active sub-cell and its 2 neighboring active sub-cells (angular adjacent) is not greater than $2\pi/3$. As proved in the TENT rule [FGG02], a node is not a local minimum when there is no angle spanned by a pair of its angularly adjacent neighbors greater than $2\pi/3$. In GAF&Co, as long as every sub-cell has at least one sensor node, local minimums can be eliminated and geographic routing with greedy forwarding can be simply applied.

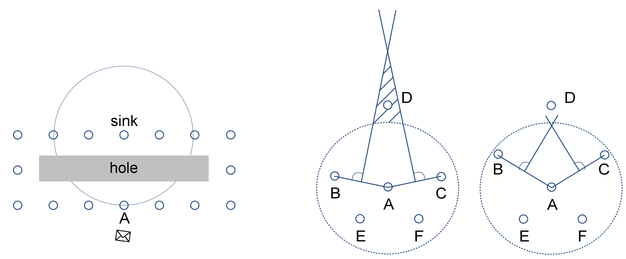

Figure 3: (a). An example of local minimum (node *A*). (b). An example of TENT rule. When $\angle BAC$ is greater than $2\pi/3$ (left figure), the perpendicular bisector of *BA* and *CA*, together with the communication bounder of node *A*, forms a shadowed area outside the transmission range of node *A*, where a point is closer to node *A* than to node *B* or node *C*. When a packet with a destination (e.g. node *D*) in the shadowed area arrives, node *A* becomes a local minimum since there is no neighbor closer to the destination than node *A* itself. When the minimal angle formed by 2 angular adjacent neighbors of node *A* is not greater than $2\pi/3$ (right figure), the shadowed area disappears and node *A* can always find a neighbor which is nearer to any point outside its transmission range.

Look-ahead geographic routing for smaller voids (ViP; HVP): Many ideas have been proposed to address the routing hole problem in WSNs [AKJ05]. To improve the success rate of geographic routing for sparsely-deployed WSNs or WSNs with small routing holes, we proposed the Greedy Forwarding with Virtual Position (ViP) and the Greedy Forwarding with Hierarchical Virtual Position (HVP) algorithms [YLT09] [YLHST09]. The main advantage of our approaches is that the algorithms simply employ GF throughout the routing process, and inherently result in high routing efficiency as the basic GF algorithms. In the mean time, the amount of control overhead of the proposed algorithms is strictly limited.

The *virtual position* of a node is introduced as the middle point of all its direct neighbors. Each node calculates its virtual position, and broadcasts its virtual position to its direct neighbors. The information of virtual position is stored on nodes themselves and their direct neighbors. The virtual position of a node indicates how the direct neighbors are located around the node on average, hence it is a suitable metric to demonstrate the tendency of further forwarding during geographic routing.

ViP is a look-ahead geographic routing algorithm based on the coordinate system of virtual positions. ViP uses virtual positions of nodes to consider farther neighbors in the look-ahead routing process, and therefore avoids packets from going into local minimums. ViP has two variants called Greedy-ViP and MFR-ViP, which are based on the principle of the two basic GF algorithms, the Greedy [F87] and MFR (Most Forwarding progress within Radius) [TK84], respectively. An example of ViP is shown in Figure 4(a). To further improve the success rate, we extended ViP to "higher-level virtual position" that considers farther nodes (neighbors of K-Hop, K>=1) in routing. The K^{th}-level virtual position (K>=2) of a node can be iterated from the $(K-1)^{th}$-level virtual positions of the node and its direct neighbors. We also proposed HVP to use the combination of all K-level virtual positions (K>=1) and the geographic positions of nodes.

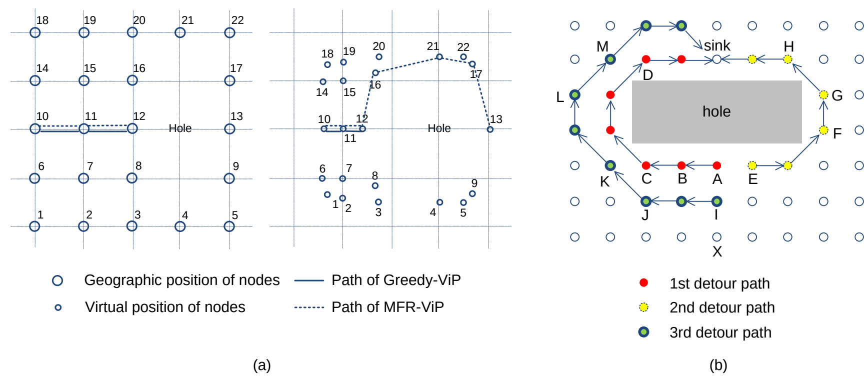

Figure 4: Classification of distributed WSNs and routing strategies (a). An example of the ViP algorithm. For a packet from node 10 to node 13, both Greedy and MFR get stuck at node 12, since there is no neighbor that can make further progress towards the destination. In contrast, the virtual position of node 12 is strongly left-biased due to the void on the right side of node 12. As a result, MFR-ViP finds a path (10-11-12-16-21-17-13) around the hole using virtual positions of nodes. (b). An example of the HobyCan algorithm, where 3 detour paths are constructed around a routing hole.

Routing path construction for large voids (HobyCan): To lead packets around large routing holes, we proposed a novel geographic routing algorithm "HOle-BYpassing routing with Context-AwareNess (HobyCan)" [YLRT09]. Our algorithm dynamically constructs multiple detour paths around routing hole(s) and uses them alternatively for routing.

HobyCan protocol is designed for the common "many-to-one" communication model of WSNs, where packets are sent from sensor nodes towards a single data sink. Therefore, detour paths are constructed from a local minimum up to the data sink. As in Figure 4(b), detour paths are disjoint from each other, while packets can be transferred from one detour path to another based on the context of the network. For packet routing around a hole, a suitable path can be dynamically determined from the set of detour paths. As a result, the energy consumption is fairly distributed with more nodes on extra detour paths. Such mechanism aims at finding optimal routing paths, as well as balancing of routing load among sensor nodes.

3 Conclusion

In this paper, we analyze the properties of WSNs from the system perspective, and classify them into different categories. In order to manage the resources (e.g. battery power, bandwidth, etc.) in WSNs, we review the clustering and routing algorithms in our former work, and apply them to meet the characteristic of WSNs of each category. The objectives of our management strategies are prolonging the lifetime of WSNs, meeting the QoS, and achieving scalability for large-scale networks.

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