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Joint design of hierarchical topology control and routing design for heterogeneous wireless sensor networks

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ABSTRACT

The heterogeneous wireless sensor networks are usually comprised by a large number of inexpensive sensor nodes, which sample the important data from the deployment position and then transmit them to their affiliated base stations in cooperative manner. Hierarchical topology control i.e., clustering technique in such networks can effectively use the limited resources of sensor nodes and prolong the network lifetimes. However, as to the classical clustering techniques, the topology controlling technique and data routing design are usually implemented by separating these two closely correlated counterparts into two independent processes. As a result, although such considerations can effectively simplify the algorithm design, it is not often the optimal solutions for improving the network performances e.g., maximizing the network lifetimes or optimizing the data rate on each link. The network components i.e., base station and sensor nodes have different features This paper proposes a unified resolution that incorporates all the above considerations as an overall decision and planning procedure. The evolution of the decision and planning procedure is analyzed via detailed examples in both simulated and real environment. Experimentation shows that our joint design approach has excellent overall deployment and allocation for member nodes and cluster heads, which is very close to the optimal solution.

1. Introduction

With the increasingly developed computer network technologies, it is feasible to build sensor networks in massive scale [1]. Once the energy suppliers equipped with network nodes are randomly scattered over sensing region, sensor nodes make individual decisions about constructing network topology, medium access control, and route finding without external aid. This necessitates devising innovative energy-efficient solutions to prolong network lifetimes, and increase robustness against abrupt energy depletion of sensor node [1–5].

Obtaining hierarchical topology in WSNs is a worthy of study problem [6]. To obtain intact sensing results, clustering for heterogeneous WSNs needs to try its best to prolong the maximum survival duration of the energy overuse node. It is noted that intra-cluster data routes have significant impacts on the energy use of bottle-neck node, because energy consumption for member node are related to two factors, topology formation and flow rate distribution.

Akyildiz et al. [7] discussed the state-of-the-art and the major research challenges in the architectures, algorithms, and protocols for wireless multimedia sensor networks. Existing solutions at the physical, link, network, transport, and application layers of the communication protocol stack were investigated. Finally, fundamental open research issues were discussed, and future research trends in this area are outlined. Akyildiz et al. [8] described the concept of sensor networks which has been made viable by the convergence of micro-electro-mechanical systems technology, wireless communications and digital electronics. First, the sensing tasks and the potential sensor networks applications were explored, and a review of factors influencing the design of sensor networks was provided. Then, the communication architecture for sensor networks was outlined, and the algorithms and protocols developed for each layer in the literature were explored. Rashid and Rehmani [9] have chosen WSN deployment in an urban environment as application scenarios. As each application scenario was different from the other, therefore WSN solution for each application had to be adaptive and innovative. They have discussed each application of WSNs in urban areas in detail with all the problems related to it and in the end, technical solution to those problems has been discussed. Wang et al. [10] performed a topology analysis of the WSNs for sandstorm monitoring. Four types of channels of sensors during sandstorms are analyzed, which include air-to-air channel, air-

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to-sand channel, sand-to-air channel, and sand-to-sand channel. Based on the channel model solutions, a percolation-based connectivity analysis is performed. It is shown that if the sensors are buried in low depth, allowing sensor to use multiple types of channels improves network connectivity. Accordingly, much smaller sensor density is required compared to the case, where only terrestrial air channels are used. Through this topology analysis a WSN architecture can be deployed for very efficient sandstorm monitoring.

Since ad hoc and sensor networks can be composed of a very large number of devices, the scalability of network protocols is a major design concern. Furthermore, network protocols must be designed to prolong the battery lifetime of the devices. However, most existing routing techniques for ad hoc networks are known not to scale well. On the other hand, the so-called geographical routing algorithms are known to be scalable but their energy efficiency has never been extensively and comparatively studied. In a geographical routing algorithm, data packets are forwarded by a node to its neighbor based on their respective positions. The neighborhood of each node is constituted by the nodes that lie within a certain radio range. Thus, from the perspective of a node forwarding a packet, the next hop depends on the width of the neighborhood it perceives. Melodia et al. [11] proposed an analytical framework to analyze the relationship between the energy efficiency of the routing tasks and the extension of the range of the topology knowledge for each node. A wider topology knowledge may improve the energy efficiency of the routing tasks but increases the cost of topology information due to signaling packets needed to acquire this information. The problem of determining the optimal topology knowledge range for each node to make energy efficient geographical routing decisions is tackled by integer linear programming. It is shown that the problem is intrinsically localized, i.e., a limited topology knowledge is sufficient to make energy efficient forwarding decisions. The leading forwarding rules for geographical routing are compared in this framework, and the energy efficiency of each of them is studied. Moreover, in the existing literature [11], a new forwarding scheme, partial topology knowledge forwarding (PTKF), is introduced, and shown to outperform other existing schemes in typical application scenarios. A probe-based distributed protocol for knowledge range adjustment (PRADA) is then introduced that allows each node to efficiently select online its topology knowledge range. PRADA is shown to rapidly converge to a near-optimal solution. To this end, Akhtar and Rehmani [12] described various battery recharging techniques and their applications with respect to WSN. They also discussed formidable issues, challenges and future research directions.

The problem that we address in heterogeneous WSNs have unique requirements that distinguish it from classical clustering problems. In classical clustering problems, clustering and data routing are usually separated as two independent items. In another word, clustering constructs topology basis for data route discovery. The essential operation in clustering is actually to select a set of CHs among nodes, and then clusters the rest of the nodes with these heads. Once clustering completes, member node transmits sensing information to CH. However, if clustering is driven by heuristics, e.g., shortest distance, random selection, Lowest ID [13], highest degree [14,15], etc., it is difficult to ensure the optimal clustering results i.e., best hierarchical network topology. With this non-optimal topology formation, although we can schedule the optimal data routes within available cluster, it is in fact not the expected performances.

In the paper, clustering and data routing are modeled in the joint consideration of a mutual coupling problem. It is expected that the longest network lifetime is obtained while clustering and data route achieve their optimal (or near optimal) states simultaneously. To decouple these two closely correlated schemes, the match problem between MN and CH (i.e. affiliation relationship) is characterized using the discrete variables {0,1}, while intra-cluster traffic is modeled as continuous variable. Thus, joint MN-CH matching and intra-cluster routing can be solved in process of distributed group decision.

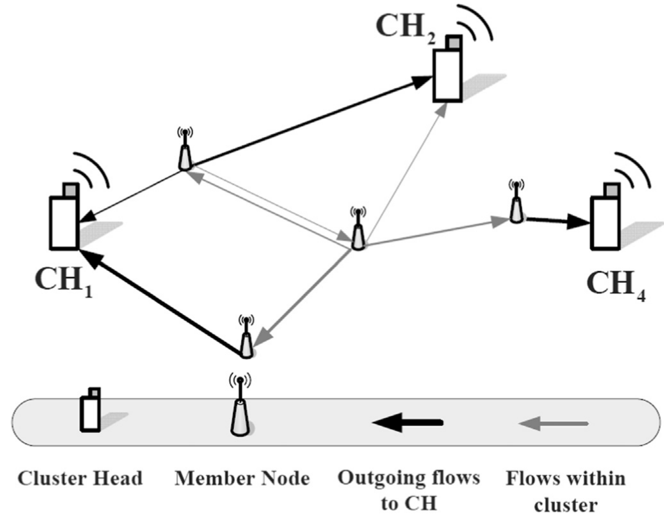

Fig. 1. Hierarchical architecture for WSNs.

Correspondingly, a mixed integer nonlinear programming optimization problem is proposed. Such a mixed integer nonlinear optimization problem is NP-hard in general. To have a deep look at the clustering and routing, a suboptimal solution is developed. As far as we know, the technical contribution of the paper has at least the following points: 1) it is the first model to couple both clustering and data routing in a joint framework; 2) a match problem between MN and CH is proposed; 3) the joint MN-CH matching and intra-cluster routing problem is resolved in the process of distributed group decision.

The rest of paper is organized as follows. In Section 2, we introduce the network models, and describe power consumption behavior of MNs. Then, we formulate the coupled MN-CH matching and intra-cluster routing problem in Section 3. In Section 4, a framework for problem modeling is proposed, while under this framework clustering process evolves until network lifetimes are approached in gradual. Extensive simulations and performance evaluations are given in Section 5. Other ongoing issues and directions for future research are concluded in Section 6.

2. Network model and background

Fig. 1 shows the hierarchical network architecture. In the scenario, a number of member nodes are randomly distributed. Each member node generates sensing information with constant data rate. Our goal is to help member nodes match with their cluster heads, and establish optimum data routes within such matched pairs. To do so, member nodes cooperate with each other in either probable bi-directional transmission or they communicate with cluster head without relay.

2.1. Clustering definitions

The notations and definitions used in this paper are listed in Table 1.

Definition 1. *(Clustering Principle)*: In WSNs, for member node set M ($M\neq\varnothing$) and cluster head set C ($C\neq\varnothing$), they form the aggregate N, where $N=C\cup M$. As there exists one mapping function f: $N\rightarrow C$, i.e. $f(N)=C_1(C_1\subseteq C,\ C_1\neq\varnothing)$, mapping function f is defined as one kind of clustering principle.

Definition 2. *(True Clustering Principle)*: Based on Definition 1, once there exists surjection mapping function $f(N)$ i.e. $f(N)=C$, and it makes any element CH_i in C satisfy both conditions $f(CH_i)=CH_i$ and $f(CH_i)\neq CH_j$ $(i\neq j)$, we say that $f(N)$ follows the true clustering principle denoted as $f'(N)$.