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Joint network lifetime and delay optimization for topology control in heterogeneous wireless multi-hop networks

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ABSTRACT

The network lifetime maximization and the end-to-end delay minimization are tackled by jointly considering the two topology performance indexes in wireless multi-hop networks. Based on the existing eligibility metric for energy efficiency, as well as the new defined metrics for fair energy consumption and end-to-end delay, a new eligibility metric is modeled as ψ_{up}^{t} (or ψ_{down}^{t}). From a node's view point, the estimation over the neighboring nodes is made according to their ψ_{up}^{t} (or ψ_{down}^{t}). The Lifetime and Delay based localized Topology Control (*LDTC*) algorithm is proposed to construct the topology, in which each node keeps its k physical neighbors with maximum ψ_{up}^{t} (or ψ_{down}^{t}) as its logical neighbors. Then the Distributed Topology Symmetry (*DTS*) algorithm is proposed to enforce topology symmetry. Finally, we present the Distributed Logical Neighbor Adjustment (*DLNA*) algorithm, by which each node adjusts its logical neighbors during the interval between two successive executions of the *LDTC* and *DTS* algorithm in order to have nodes exhaust their energy fairly. The simulation results confirm that, under the most simulation settings, our topology control scheme has the minimized imbalance energy reserve and end-to-end delay when compared with the existing similar works. These results show that our topology control scheme suits to prolong the lifetime of the network and also satisfies the demand for low end-to-end delay.

1. Introduction

The area of energy-saving topology control [1–16] has attracted a great deal of attention. Nodes in a wireless multi-hop network collaboratively determine their transmission power and define the network topology by forming the proper neighbor relation under the constraint of network connectivity and the criteria with respect to energy efficiency. However, from the network's point of view, it may not be sufficient for the overall network performance due to the lack of delay [17,18] or network lifetime [19–21].

The wireless sensor networks enable the monitoring of a variety of environments for applications. Unlike in cellular networks where it is sufficient that each node be connected to a base station, communication between two nodes in a wireless sensor network is multi-hop, extending the reach of the devices. Thus every node, in addition to being a source or a destination, is also a relay node, forwarding packets of other nodes. These networks should function for as long as possible. It may be inconvenient or impossible to recharge node batteries. Some nodes may become dysfunctional when they may exhaust their energy more rapidly than others. Therefore, all aspects of the networks, especially topology performance, must be designed to be extremely long network lifetime.

The some works [22,23] are mainly concerned about network lifetime. However, the other works [24,25] consider both energy efficiency and network lifetime. The work in [24] assumes that each node has the same initial energy, while the work in [25] supposes that it has the same transmission range and sufficient battery power. Furthermore, the work in [24] takes energy efficiency and network lifetime into account in the topology construction phase since it only focuses on this phase, while the work in [25] only considers how to balance the consumed energy to prolong network lifetime in the maintenance phase after topology construction.

In practice, once a topology is generated, it is ready for use. Moreover, it is more cost-efficient to maintain a generated topology during its usage. Therefore, the topology performance indexes had better be considered at the same time as early as possible, in which the work in [24] is better than that in [25]. However, there are also some problems in [24], which are described through the following example.

In Fig. 1, the node u is far away from the Base Station (BS), so it wants to select the best relay to forward its data packets to BS according to a given criterion. The node v, w, x, and y may be regarded as the potential relays, where, take the node v for

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example, the symbol e_v and E_v denote its remaining energy and initial energy reserve respectively. If only energy efficiency is considered as the selection criterion of the node u, the node w is selected as the best relay since it is closest to BS (see Section 3.2 for the detail).

Also, the node u will select anyone of the node v and y if it considers both energy efficiency and network lifetime as the selection criterion. Since e_v/E_v or e_y/E_y is much more than e_w/E_w, the unbalanced energy consumption can be greatly lowered. Although the corresponding energy efficiency is slightly bad due to the slightly long distance between the selected relay and BS, the comprehensive performance is better (see Section 3.2 for the detail). However, they will not hold in some scenarios.

First, when the distribution of initial battery capacity is uneven, the above methods will get an inappropriate relay (i.e. either of node v and y), which is not helpful in reducing average remaining energy variance. For example, if the initial energy of node w is 0.2 J and those of node x, v and y are 0.5 J, 0.1 J and 0.1 J respectively, the best relay should be node x instead of node v or y.

Second, the above methods may suffer from a high variation in end-to-end delay. Since anyone of node v and y is regarded by node u as its best relay, it can use either of them. When there are the great differences between the two relays in terms of the packet forwarding capacity and the number of interference sources, the different selection will lead to the high variation in end-to-end delay.

Third, a node may select a relay with high delay according to the above methods. For example, assume node y have the lower packet forwarding capacity and the more number of interference sources than node v, and also let its e_y/E_y be 1.0, only node y will be selected by node u as its 'best relay', which is actually very bad in terms of end-to-end delay. On the other hand, there is also the opposite case. These cases are likely to occur in a random manner, which causes the fluctuation of end-to-end delay.

With the development of Wireless Multimedia Sensor Networks (WMSNs), they will not only enhance traditional sensor network applications, but also enable several applications with rigorous delay-constraint, such as multimedia surveillance for forest fires. Therefore, not only fair energy consumption but also other metrics such as latency and jitter are primary concerns in mainstream research on WMSNs. However, although delay constraint is considered in some literatures [17,18], network lifetime is ignored.

In order to address the above problems, we propose a new localized topology control scheme that enables nodes to jointly optimize link lifetime and link delay under the constraint of network connectivity and energy efficiency based on the new defined eligibility metric in this paper, which is more efficient when the initial energy distribution of nodes is not balanced.

Our scheme is different from those in [24,25] based on the following aspects: (1) it takes the uneven characteristics of nodes' initial energy reserve into account to define a new metric model, while the works in [24] assume that all nodes start with equal initial battery capacity; (2) it aims to jointly reduce the delay and unbalanced energy consumption of any multi-hop link based on local knowledge while improving energy efficiency, the works in [24] only reduce unbalanced energy consumption of any multi-hop link besides considering energy efficiency; (3) there is the logical neighbor adjustment process during the interval between two successive executions of the topology control protocol in our scheme, while not only the works in [24] but also the other related works never include this process; (4) unlike the works in [25], it has no such some assumptions that nodes have the same transmission range and sufficient battery power, and attempts to reduce unbalanced energy consumption in both construction and maintenance phase for network topology.

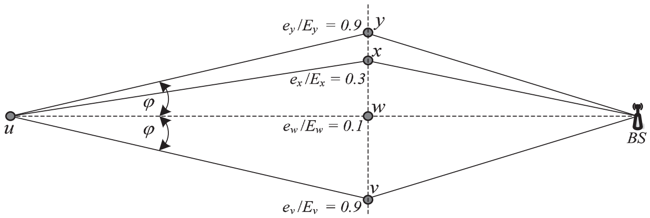

Fig. 1. An example for relay selection.

There are also some main differences between our current work and our previous work [18] as follows: (1) the current work considers energy efficiency, fairly energy consumption and delay, while the previous work only focuses on the tradeoff between energy efficiency and delay; (2) the current work jointly consider the three performance indexes to model a new eligibility metric for nodes, which is the form of multiplication model, while the previous work jointly consider the two performance indexes to model a weight sum formula for links, which is the form of addition model; (3) the current work is a type of neighbor-based method, while the previous work belongs to the methods based on geometric proximity graphs.

The rest of the paper is organized as follows: First, we discuss related work in Section 2. In Section 3, the network model and its basic assumptions are outlined. In Section 4, the proposed scheme is discussed in detail, including the eligibility criterion for ensuring both a fair utilization of energy and low link delay in wireless sensor networks, and the algorithms for executing the topology control protocol. In Section 5, the simulation settings and results are shown and analyzed. Finally, in Section 6, we provide concluding remarks.

2. Related work

Most existing topology control schemes apply geometric proximity graphs (such as Relative Neighbor Graph (RNG) [1], Gabriel Graph (GG) [2], Delaunay triangulation graph [3], and Minimum Spanning Tree (MST) [4]) to build sparse, but connected links, such as [5–14].

Borbash et al. [5] propose to use RNG for the topology initialization of wireless networks, in which each node makes decisions to derive the network topology according to its local knowledge. Wan et al. [6] provide some asymptotic results on the length of the longest edge of the GG under all nodes have the same maximal transmission radii, which is the critical transmission radius such that the GG can be constructed by localized and distributed algorithms using only 1-hop neighbor information. $LDel^{(k)}$ [7] is a local version for the algorithm inducing Delaunay triangulation graph, which requires nodes to collect k-hop neighbor information.

The work in [8] is based on the Local Minimum Spanning Tree (LMST), which only requires each node to collect its 1-hop neighborhood information to build its local minimum spanning tree respectively, and only keeps on-tree nodes that are 1-hop away as its neighbors in the final topology. Directed Relative Neighborhood Graph (DRNG) and Directed Local Minimum Spanning Tree (DLMST) [9] can be directly applied to heterogeneous wireless networks, in which only 1-hop neighborhood information is requested by each node to build its local proximity graph.

The XTC [10] uses the notion of link quality in making its topology control decision, and reduces to the DRNG when link quality between two nodes is measured by the energy cost of a transmission between them. The Step Topology Control (STC) algorithm [11] may be seen as an extension of the DRNG algorithm, and its allowed information exchange range is 3-hop neighborhood.

The r-neighborhood graph [12] is a general structure of both RNG and GG, which can be adjusted between the two objectives through a parameter r. The literature [13] extends the r-neighborhood graph to mobile environments further. A t-adjustable planar