Digital Communications and Networks (2016) 2, 1–14

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Topology control of tactical wireless sensor networks using energy efficient zone routing

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Received 12 June 2015; received in revised form 3 December 2015; accepted 12 January 2016
Available online 28 January 2016

KEYWORDS
Routing;
Energy efficiency;
Wireless sensor networks;
Zones;
Topology control

Abstract
The US Department of Defense (DoD) routinely uses wireless sensor networks (WSNs) for military tactical communications. Sensor node die-out has a significant impact on the topology of a tactical WSN. This is problematic for military applications where situational data is critical to tactical decision making. To increase the amount of time all sensor nodes remain active within the network and to control the network topology tactically, energy efficient routing mechanisms must be employed. In this paper, we aim to provide realistic insights on the practical advantages and disadvantages of using established routing techniques for tactical WSNs. We investigate the following established routing algorithms: direct routing, minimum transmission energy (MTE), Low Energy Adaptive Cluster Head routing (LEACH), and zone clustering. Based on the node die out statistics observed with these algorithms and the topological impact the node die outs have on the network, we develop a novel, energy efficient zone clustering algorithm called EZone. Via extensive simulations using MATLAB, we analyze the effectiveness of these algorithms on network performance for single and multiple gateway scenarios and show that the EZone algorithm tactically controls the topology of the network, thereby maintaining significant service area coverage when compared to the other routing algorithms.

1. Introduction

A Wireless Sensor Network (WSN) is a group of autonomous sensor nodes that are geographically distributed to gather data and monitor events. WSNs are finding increased applicability to the Department of Defense (DoD) in areas specific to surveillance and reconnaissance. A tactical WSN is used in a remote geographic location in order to monitor deployed systems and trigger alerts at a Command-and-Control (C&C) site when

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Peer review under responsibility of Chongqing University of Posts and Telecommunications.

http://dx.doi.org/10.1016/j.dcan.2016.01.002

certain events occur. Each sensor node in the WSN must have the ability to simultaneously serve as a sensing device and a wireless communication device that can exchange information with nearby nodes [1]. The gateway serves as the destination for a node's packets is the bridge between the tactical WSN and the backbone infrastructure which includes the C&C site. Because the gateway is a significant component of the WSN architecture, its location must be considered. We focus our attention toward gateway locations on the periphery of the sensor field. For tactical WSNs, we assume that a location on the periphery is more likely to be a safe zone compared to where the sensor nodes are deployed. Our use of safe zone refers to a location where the gateway is outside normal environmental and physical constraints to which sensor nodes may be subjected.

In this paper, we investigate two types of tactical WSNs: (1) a single gateway scenario and (2) a multi-gateway scenario. The majority of existing research on WSNs generally includes the perspective of a single gateway [1-5]. The few works that study multigateway sensor networks focus on reliable routing, not taking into consideration the energy efficiency requirements of the sensor nodes [6,7]. Thus, it is important to extend WSN concepts to a multi-gateway framework and identify the resulting performance improvements by including an additional gateway.

1.1. Deployment challenges of tactical WSNs

A tactical WSN must operate reliably and increase sensor network coverage for as long as possible in the absence of human contact. A key challenge in the deployment of tactical WSNs is the limited battery power of each sensor node. This has a significant impact on the service life of the network. We define service life of a tactical WSN to be the amount of time that nodes are able to transmit information to the gateway without significant interruption. The service life of the network is contingent upon the network topology. As nodes begin to die out, the remaining live nodes may be disconnected from one another, undermining their ability to communicate with the gateway node. For example, if only 20% of the nodes in the network remain alive (i.e., have enough residual energy to use for transmitting, sensing and/or receiving), but they are concentrated within transmission range one another, then communications can still take place for that area. This is the preferred situation. However, with 80% of the nodes dead, the possibility of live nodes residing in areas where they are detached from one another is also possible. While this situation may also occur in a commercially used WSN, the ramifications of information not getting to the gateway may not be as severe as in a tactical WSN where important information from the battlespace is being transmitted from the sensor nodes and being used for tactical decision making. Thus, the ability to control the network topology using an effective routing algorithm is essential to ensuring that the network remains usable for the longest amount of time. In this paper, topology control refers to the ability of the routing algorithm to ensure that nodes with residual energy in one or more areas remain connected to one another and/or the gateway for continued data transfer.

1.2. Motivations and contributions

Energy efficient routing is not a new topic in WSN research. Extensive studies have been conducted in this area [1,2,8-14]. Many of these works offer modifications to already well established WSN routing algorithms. Both [12] and [13] provide algorithms for the modified Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm [2]. In addition, [10,11,14] and [15] develop algorithms based on the idea of clustering. Clustering is a common hierarchical routing procedure implemented in WSNs. The idea is that energy consumption is reduced by allowing only a select number of nodes, known as Cluster Heads (CH), to aggregate data from member nodes and transmit to the gateway. A disadvantage with clustering is the CH election process. Depending on the type of procedure used, CHs may be elected such that they reside on the opposite end of the network [16]. This situation is common in LEACH where CHs are elected randomly based on a probability model. This means that an elected CH may not be physically close to node members. This then nullifies any energy savings that clustering achieves. There have been various modifications to LEACH in recent years, including improvements to LEACH security [17]. However, the fundamental CH election procedure remains the same, exposing the problem of CH election as mentioned above.

There has been some work that has been done on tactical WSNs that serve as a foundation for our work [18,19]. While [18] and [19] provide architectural constraints for tactical WSN deployment, the routing process and its impact on network topology is not discussed. In [20], the authors develop a cross layer load balancing/routing scheme for tactical WSNs. However, the authors do not provide an in depth analysis on the impact of tactical topology control when using load balancing and routing algorithms.

In this paper we show traditional routing algorithms that are regularly used in commercial WSNs have a negative impact on the service life of a tactical WSN because their design is not meant to meet the requirements of tactical WSN applications. More specifically, we extend our work in [20] by showing that established routing algorithms regularly seen in the literature do not effectively control the topology of the network. We aim to provide realistic insights on how an energy efficient routing algorithm can increase service life by tactically controlling the network topology. To the best of our knowledge, this is the first work to provide an extensive analysis of how different routing algorithms impact the operational capability of a tactical WSN.

Our contributions in this paper can be summarized as follows:

- Develop a novel energy efficient zone routing algorithm that tactically controls the network topology. We call this algorithm EZone. We identify performance improvements of EZone and compare it to the following established routing techniques: (1) Direct Routing, (2) Minimum Transmission Energy (MTE), (3) Low Energy Adaptive Clustering Hierarchy (LEACH), and (4) Zone routing. We also identify performance improvements of adding an additional gateway to these algorithms.
- As sensor-node battery levels are depleted and nodes subsequently die out, we show how EZone affects the topology of live nodes and dead nodes in the sensor field