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Autonomous management of a recursive area hierarchy for large scale wireless sensor networks using multiple parents

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ABSTRACT

Large scale, duty-cycled, wireless sensor networks provide support for applications ranging from anomaly detection to vehicle tracking. In order meet the requirements of these applications an autonomous configuration and maintenance method that is efficient and effective is required. When selecting a management solution it is important to consider both the direct and indirect costs associated with the different solution. For example, the overhead associated with communication synchronization and scheduling is an example of an indirect cost that can significantly impact the network lifetime. Further, an effective solution needs to recognize that in-network data aggregation and analysis presents significant benefits and should configure the network with a structure that benefits application layer functions. NOA, the proposed network management protocol, utilizes a multi-parent hierarchical logical structure. The multi-parent structure provides application layer functions with significant inherent benefits such as, but not limited to: elimination of the single-parent network divisions, data resolution guarantees when comparisons are performed at data aggregation points, and redundancies for communication as well as in-network data aggregation, analysis and storage.

1. Introduction

Large-scale wireless sensor networks (WSNs) utilize a large number of sensor devices spread across a vast geographic area and can support a wide range of applications including but not limited to environment/habitat monitoring, area intrusion detection, and person/vehicle tracking [1–6]. Unreliable low-power wireless communication links, and ever changing environment and the uncertainty of if a node in the network has moved, run out of power, or possibly been damaged creates a dynamic network topology. As such, network management techniques must be able to autonomously configure and re-configure the network to self-heal the mesh network.

Autonomous setup and configuration significantly reduces the amount of human effort and error involved with the deployment of a large scale WSN and decreases the monetary cost of deploying and maintaining the communications for WSNs. Shifting these tasks from manual labor to an autonomous protocol requires computational and communication resources be utilized to perform the work. Many wireless sensor devices are battery powered or use some form of energy harvesting and as such need to minimize the resources used to manage a network as these resources can have a significant impact on a network's lifetime. Traditional management solutions rely on flooding the network to maintain communication paths which is extremely inefficient. The motivation for the proposed solution includes but is not limited to (1) increasing

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the robustness by introducing redundancy, (2) provide a solution capable of in-network, multi-resolution analysis that has overlapping clusters to support enhanced anomaly detection and tracking protocols, and (3) remove the flooding algorithms that are present in the traditional solutions for autonomous network construction and maintenance.

A wireless sensor node includes constrained resources including limited power reserves, computational power, and communication bandwidth. As such, it is necessary to utilize a scalable solution to autonomously organize sensor devices that promotes radio duty cycling, efficient and effective routing, and an architecture for application layer functions (e.g. in-network data analysis, distributed hash table, query resolution [2,7–15]) to extend the lifetime of a wireless sensor network. The recursive area clustering hierarchy has been shown to be a promising scalable solution for autonomously organizing wireless sensor networks [16]. The recursive area clustering hierarchy is a logical overlay on the network that organizes the devices into a hierarchy of clusters starting with $tier-1$ clusters and recursively clustering the lower tiered clusters into a super-cluster until the top most cluster covers the entire network. In other words, $tier-1$ clusters consist of a group of devices in a given proximity, $tier-2$ clusters are composed of $tier-1$ clusters in an area exponentially larger than the $tier-1$ clusters. $Tier-3$ clusters are composed of $tier-2$ clusters and so on until the highest level $tier-N$ cluster. This type of structural overlay provides a scalable solution that is logarithmic in terms of the number of tiers in the hierarchy and can be used as a paradigm for application layer functions such as routing, multi-resolution analysis and multi-resolution data storage.

Current state-of-the-art solutions for recursive area hierarchies focus on a single-parent hierarchy (Fig. 1) where each cluster is only part of a single super-cluster. Each cluster head in a single-parent hierarchy is a single point of failure that can be removed by utilizing a multi-parent solution to increase the robustness and reliability of the network management. Management of single-parent hierarchies require the use of inefficient flooding algorithms which can be replaced when a multi-parent solution is utilized. Further, the single parent structure divides the network at each cluster into separate sub-networks. This artificially limits the capabilities of the mesh network by reducing the connectivity of the devices. The multi-parent hierarchy described herein (Fig. 2) removes the artificial limitations introduced by the single-parent hierarchies while creating a scalable structure that can be constructed, maintained and utilized at a comparable cost and in some cases a lower cost when compared to the single-parent equivalent. These divisions increase the complexity of application layer protocols because neighboring cluster's that are split by a hierarchy division do not have the ability to communicate directly with one another and as such have to rely on higher tiered cluster-heads performing the analysis on the data. Further, by the time it reaches the common ancestor the analysis is utilizing data that has been smoothed due to the effects of data aggregation and compression creating the possibility that an anomaly or event goes undetected. Multi-parent hierarchies remove the network division problem and data from neighboring cluster-heads is always compared at its common grand-parent as opposed to at the first ancestor that bridges the network division which in the worst case is the highest tiered, tier-*N*, cluster-head in the network.

2. Background and related work

2.1. Local synchronization and scheduling communications

The lifetime of a wireless sensor network is impacted by the individual devices, communication protocols, and the logical structure of the network. These are closely coupled entities that significantly impact each other. For example, the power consumption of a device can be significantly reduced by turning off (duty-cycling) a device's radio, sensors and/or the entire device when the components are not needed. However, turning off a device's radio has significant impacts on communication, as neighboring devices must be turned on in order to communicate which requires some form of synchronization and scheduling. The logical structure of a network and the protocols used to generate that structure can require different levels of synchronization and scheduling based on the routing mechanisms used (i.e. broadcasting, flooding, uni-cast, multi-cast). These are just a few of the many examples of coupling between the

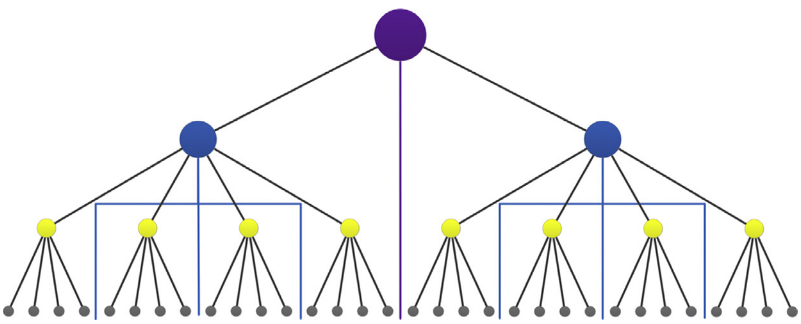

Fig. 1. A conceptual representation of a single-parent hierarchy. The single-parent clustering creates a single point of failure at each cluster-head and divides the network into separate groups that cannot share information among neighboring clusters without traversing the hierarchy and communicating through the common ancestor. This makes it more difficult for a cluster to compare its information with all of its neighboring clusters as it only has direct access to those within its super-cluster.