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Delay characterization and performance evaluation of cluster-based WSN with different deployment distributions

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HIGHLIGHTS

- We demonstrated the key role of BS location selection for random topology to fulfill the application mission.
- Delay statistical analysis captures the intrinsic properties of the main delay components.
- Real-time applications should examine the instantaneous delay and not only depend on the average values.
- A tradeoff should be considered between the energy utilization efficiency and the required amount of data/coverage.

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ABSTRACT

Provisioning of quality of service (QoS) is the ultimate goal for any wireless sensor network (WSN). Several factors can influence this requirement such as the adopted cluster formation algorithm. Almost all WSNs are structured based on grouping the sensors nodes into clusters. Not all contemporary cluster formation and routing algorithms (e.g. LEACH) were designed to provide/sustain certain QoS requirement such as delay constraint. Another fundamental design issue is that, these algorithms were built and tested under the assumption of uniformly distributed sensor nodes. However, this assumption is not always true. In some industrial applications and due to the scope of the ongoing monitoring process, sensors are installed and condensed in certain areas, while they are widely separated in other areas. Also unlike the random deployment distributions, there are many applications that need deterministic deployment of sensors like grid distribution. In this work, we investigated and characterized the impact of sensor node deployment distributions on the performance of different flavors of LEACH routing algorithm. In particular, we studied via extensive simulation experiments how LEACH cluster formation approach affects the delay (inter and intra-cluster delay) and energy efficiency expressed in terms of packet/joule for different base station locations and data loads. In this study, we consider four deployment distributions: grid, normal, exponential and uniform. The results showed the significant impact of nodes distribution on the network energy efficiency, throughput and delay performance measures. These findings would help the architects of real time application wireless sensor networks such as secure border sensor networks to design such networks to meet its specifications effectively and fulfill their critical mission.

1. Introduction

A wireless sensor network (WSN) consists of spatially distributed autonomous and battery-powered sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants and to cooperatively pass their data through the network to a main location (i.e., base station or sink). In recent years wireless sensor networks have a wide range of application; such as battlefield surveillance in military applications, industrial process automation (monitoring and controlling), meteorological areas, home appliances, and health applications [1]. However, wireless sensor nodes have limited resources in terms of processing, storage, and communication capabilities and using existing routing protocols for ad-hoc networks is not

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efficient. Therefore, power-aware routing protocols have been proposed and several surveys and comparison studies have been conducted [2–4].

All these studies have explored the performance of routing protocols under the assumption of uniformly distributed or deployed sensor nodes in the area of interest. However, this assumption is not always true especially in industrial networks where the ongoing applications determine the location of a sensor node to monitor and control a specific region or a machine, whereas in military applications it might be deployed by throwing them from a plane that may resemble a normal distributed scenario. Therefore, it is important to study the impact of random distributions other than uniform distribution on the specific routing protocols.

The contributions of this work are three fold. First, we studied the impact of three random deployment distributions of sensor nodes namely normal, uniform and exponential as well as grid deployment strategy on the performance of the LEACH and its extension LEACH-C [5–7]. To the best of our knowledge, this issue has not been investigated well in the literature. Second, this work also investigated the behavior of these routing protocols under real scenarios of data availability for transmission in each sensor node. Most of the existing studies assume that the sensor always has data to send which makes the network fully loaded during the whole network lifetime. However, in practical WSN, the sensors vary from each other in data transmission rate based on the ongoing mission. For example, in motion detection application, the region surrounding the intruder penetration may need to transmit more packets than the one that is far away. This paper has studied the effect of different data rates on WSN routing protocols and how that influences the network performance. The third part of this study concentrated on delay characterization for cluster based WSN. Since this is an important measure for improving the real time systems design, we have investigated the inter and intra delays of clusters under different situations and conditions by varying network density and deployment strategy.

The rest of this paper is organized as follows. Section 2 discussed the related work and briefly describes LEACH and LEACH-c routing protocols. Section 3 discusses the different scenarios that are used in our study including the different combinations of different distributions with different base station locations (i.e. corner or center). Simulation setup and result analysis are presented in Section 4. We conclude our paper in Section 5 with a summary of findings and a brief discussion of future work with open research issues.

2. Related work

Some non-uniform deployment strategies have been studied in past published works. However none of them has studied the impact of these distributions on WSN routing protocols. Lian et al. [8] focused on increasing the total data capacity by only considering the energy spent on the data transmission. They found that in a uniformly distributed homogeneous WSN with a static base station, after the lifetime of the network is over, up to 90% of the total initial energy remains unused. They proposed a non-uniform sensor distribution strategy by adding more nodes to the heavier energy load area, and thereby maximizing the network lifetime by balancing the energy consumption over nodes. Their simulation showed that the strategy can increase the total data capacity by an order of magnitude.

Wu et al. [9] also addressed the energy hole problem in WSNs with non-uniform node distribution. They investigated the theoretical aspects of the non-uniform node distribution strategy, which aim to avoid the energy hole around the sink. They assumed that each sensor generates data for each data collection period, which may not be true for highly dense WSNs. They provided a non-uniform node distribution strategy, which makes the number of nodes increases with geometric proportion from the outer parts to the inner parts of the network, which looks like normal distribution. Simulation experiments demonstrated that when the network lifetime has ended, the nodes in the inner parts of the network achieve nearly balanced energy depletion, and only less than 10% of the total energy is wasted. Liu et al. [10] proposed a non-uniform deployment scheme based on a general sensor application model. They derived a function to determine the number of nodes as a function of the distance from the sink. They also assumed that each sensor is required to report the data back to the sink. Simulations show that their method can enhance the network lifetime.

All these non-uniform deployment strategies focused on accurately controlling the location of sensors in the network domain for achieving a higher lifetime. In some real applications, it is hard to strictly control the number of nodes in a given domain, e.g., the sensors that are dropped from a helicopter or a low-flying unmanned aerial vehicle. Zou and Chakrabarty [11] suggested the placement of airdropped sensors as 2D Gaussian distribution without giving any specific results. Wang et al. [12] argued that an appropriate strategy can be employed when dropping sensors from a plane to have the standard deviation of the 2D Gaussian distribution. For instance, this can be performed by controlling the height of the plane or using some specific devices to eject sensors with different circular angles. Therefore, distribution of sensors could satisfy 2D Gaussian distribution and follows a predefined standard deviation with the center point at the drop point of the helicopter. This enables sensors to have a higher probability to be deployed near the drop point than the uniform deployment. The benefit of it is that this relaxes the energy hole problem and increases the WSN lifetime.

Wang et al. [12] investigated the Gaussian distribution as a deployment strategy in WSNs. Their study was focused on two important design factors: deployment strategy, and the lifetime and coverage. In this work, they have provided theoretical formulations for lifetime and coverage in a WSN based on 2D Gaussian distribution. Two types of dispersions are considered. $\sigma x = \sigma y$ and $\sigma x \neq \sigma y$. The analytical model captures the intrinsic properties of the coverage and the lifetime by using various parameters. They showed that the Gaussian distribution can effectively increase the lifetime. The analytical results could serve as the WSN design guideline. For this purpose, they have developed two algorithms to compute the optimal deployment strategy and show that the optimal deployment strategy can be obtained in a polynomial time complexity. Although they came out of the general nature of previous studies by including a non-uniform distribution in their study, their study did not show the impact of Gaussian distribution deployment on the existence WSN routing protocols, e.g. LEACH.

Wu and Chen [13] proposed a partition-based hybrid clustering routing protocol (named PHCR). To address the problem that the cluster-heads are distributed unevenly in the network, they divided the network monitored area into several sectors through the partition algorithm. In the first round, the sensor node which is the nearest to the area center is selected as the cluster heads by the sink node, and the other nodes in each sector become the member nodes. The sensor node which is the second closest to the sector center is selected as the cluster head for the 2nd round. After the 2nd round, the cluster head of the next round is chosen by the prior cluster head of its own cluster. Simulation results showed that PHCR has improved the network lifetime effectively.

Sara et al. [14] studied the effect of node distributions on lifetime of WSNs. Unlike our study, they focus on prolonging the network lifetime by investigating different node deployments including both geometric and uniform. Geometric distributions are represented by star topologies with different variations of number of star brunches and number of nodes in each brunch. They found