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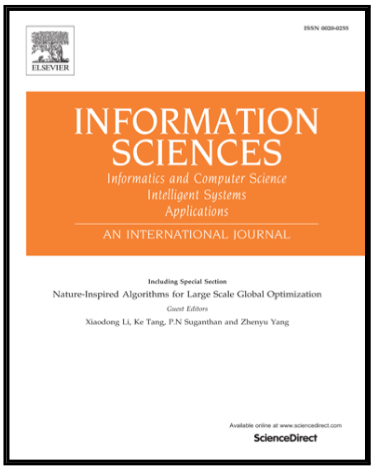

Optimal Relay Placement for Lifetime Maximization in Wireless Underground Sensor Networks

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Optimal Relay Placement for Lifetime Maximization in Wireless Underground Sensor Networks

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***Abstract*—Because of highly lossy underground channels and the difficulty in recharging the buried sensor nodes (SNs), power conservation is a primary objective in the design of wireless underground sensor networks (WUSNs). One promising approach to prolonging the lifetimes of WUSNs is to deploy aboveground relay nodes (RNs) to relay the traffic. However, there are several challenges. First, the candidate locations of RNs are affected by the terrestrial environment. Second, signal attenuation is complex because of the multimedium propagation. Third, the optimal placement problem has to be considered in a three-dimensional space. Finally, load balancing among RNs is required to ensure that there is no overloading or exhausting of a single node. In this paper, the RN placement problem in WUSNs is modeled and formulated for the first time; the goal is to deploy a limited number of RNs to maximize the lifetimes of WUSNs under system constraints, such as locations, load balancing, network topology, and a practical channel model. Furthermore, the problem is reformulated by introducing an extra decision vector to transform the original constraints into linear constraints, and then, a two-phase method is presented to solve the problem efficiently. Extensive simulations are carried out to evaluate the performance of the proposed method.**

***Index Terms*— Wireless underground sensor network, relay node placement, lifetime maximization, load balancing**

I. INTRODUCTION

WIRELESS underground sensor networks (WUSNs) are networks consisting of underground sensor nodes (SNs) that send sensing data through soil wirelessly [1]. As an emerging technology, WUSNs enable a wide variety of novel applications, such as underground environment/infrastructure monitoring, object locating, and security monitoring [1]. However, because of highly lossy underground channels [2, 21] and the difficulty in unearthing and recharging the buried SNs, power conservation is a primary concern in the design of WUSNs.

Above ground relay nodes (RNs) have been used to extend the range of SNs, leading to a larger wireless coverage [13, 46], better wireless connectivity [28, 44] and higher network capacity [24, 34]. However, WUSN-specific design requirements, together with other traditional design constraints, make the optimal deployment of RNs very challenging.

The application scenarios of WUSNs may impose some physical constraints on the locations of the RNs [28, 44]: there may be a lower bound or a higher bound on the height of RN antennas; or there may be infrastructures that can be utilized to place RNs; or there may be some forbidden regions where RNs cannot be placed. For instance, in an application of WUSNs for monitoring soil conditions in precision agriculture [12], attaching RNs to sprinklers or trees is a cost-effective alternative to installing new antenna stands to hold RNs.

The propagation environment of electromagnetic (EM) waves is complex, as the signals travel through multilayered media (soil and air) and a medium interface [2, 21]. The signal is attenuated not only because of the absorption of each medium but also as a consequence of reflection and refraction at the medium interface, which prevents simple ray models from characterizing the channel accurately. A multimedium propagation results in a non-uniform transmission range of buried SNs, as shown in Fig. 1. Therefore, instead of using simple ray models, refraction models should be considered.

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