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Energy efficient hybrid wired-cum-wireless sensor network design

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ABSTRACT

The broad range of wireless sensor network applications has been part of the exponential growth in wireless communications and related technological developments. As a result, the concern on energy efficient network designs is increasing as the energy consumption is becoming a global environment problem. Minimizing energy dissipation and maximizing network lifetime are among main factors, aiming for optimized designs which lead to green applications. In an industrial application, various energy efficient network configurations can be designed. One such robust configuration is a hybrid wired-cum-wireless sensor network that is composed of a wireless sensor network and a wired backbone, which are inter-connected via access points. In this paper, the joint problem of configuring a hybrid wired-cum-wireless sensor network, position-constrained cluster head location, sensor nodes allocation, and position-constrained access point placement is addressed. The design considers real wireless communication limitations in the industrial applications, optimum locations of access points and cluster heads, and hybrid transmission structure of the network with the objective of minimizing the network energy consumption and configuration cost. The problem is formulated as a mixed integer non-linear programming (MINLP) model and solved with "BARON". Numerical results show that the hybrid configuration is more energy effective than the wireless networks and leads to a longer lifetime at the expense of a more complex design.

1. Introduction

The emergence of sensor networks, networks of many smart sensing, data processing, and communicating components, has enabled sensing, controlling, and monitoring of the physical phenomena conditions or variables such as pressure, motion, temperature, humidity, sound, intensity, vibration, and corrosion. Sensor networks can support a spectrum of applications ranging from academic, industrial, agricultural, domestic, and national security to military uses (Chong and Kumar, 2003, Yick et al., 2008; Bonvoisin et al., 2012; Cama et al., 2013; Chang et al., 2013). The broad range of wireless sensor network applications has been a part of the exponential growth in wireless communications and related technological developments. As a result, the concern for energy efficient network designs is increasing as the energy consumption is becoming a global environment problem. Minimizing energy (power) dissipation and maximizing network lifetime are among main factors, aiming for optimized designs which lead to green applications.

Such a robust energy efficient design is a hybrid wired-cum-wireless sensor network that is composed of a wireless sensor network and a wired backbone (e.g., high-speed multi-mode optical fibers), which are inter-connected via access points (Subramanian and Katz, 2000; Bhardwaj and Chandrakasan, 2002; Miorandi and Vitturi, 2004; Flammini et al., 2008; Wang et al., 2009; Cardenas et al., 2013; Ng and Lam, 2014) These two networks are inter-connected via Access Points (APs), which are fixed nodes that provide interfaces between the wired and wireless parts of the network (Wang et al., 2009) (see Fig. 1).

Sensor nodes are generally battery powered and communication is the dominant factor in power consumption in wireless data transmission (for more explanation, refer to Section 3.2) (Sanchez et al., 1999; Qia et al., 2001; Hou et al., 2005). Multi-hop communication is more energy efficient than single-hop since it reduces

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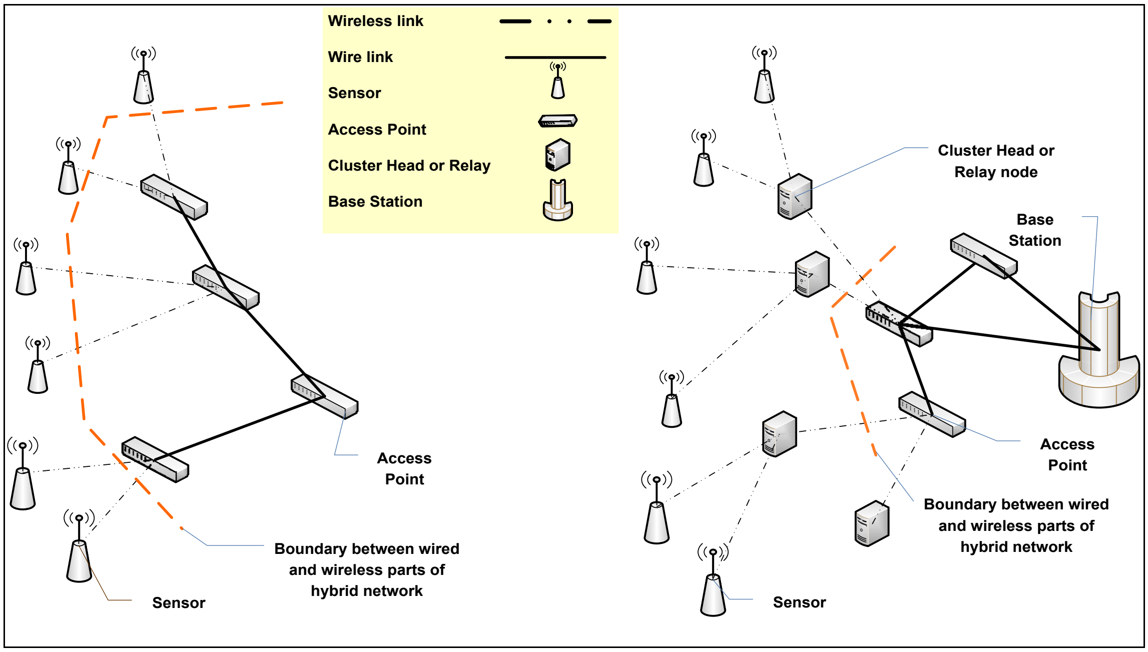

Fig. 1. A hybrid wired-cum-wireless sensor network (Subramanian and Katz, 2000).

the communication range (Chakrabarti et al., 2004). Furthermore, clustering the network using cluster heads (CHs) in hierarchical network architecture enables better management of nodes and data aggregation with lower energy consumption and leading to better performance and longer lifetime (Bandyopadhyay and Coyle, 2004; Hou et al., 2005; Abbasi and Younis, 2007).

This paper considers a multi-tiered sensor network consisting of diverse sensors distributed in the manufacturing plant and one Base-Station (BS), which is located in the control building (see Fig. 2). Sensors are distributed on equipment, machines, walls, or ceilings to sense. These sensors could be utilized to monitor pressure, motion, temperature, humidity, sound, and vibration. A known number of relay nodes in the factory space are going to be located and allocations of sensors to relays are also determined. Moreover, the locations of APs among available candidate locations are chosen, and the hybrid transmission structure of a wired-cum-wireless sensor network with the aim of minimizing network energy consumption and configuration cost is determined (see Fig. 3). Considering a fixed lifetime for the hybrid network, the wire network configuration cost is comprised of installation costs of APs and the wired backbone infrastructure in the network. Cost of energy or power consumption arising from wireless network communications in network lifetime (receiving and transmitting the data through wireless links) is considered as the wireless network cost component (Akyildiz et al., 2002; Pan et al., 2003).

Specifically, the following problem is investigated. For a given number of sensor nodes deployed in the manufacturing plant, one BS with known position, specific continuous areas to place a known number of relay nodes, and a set of discrete candidate locations in the network area, where APs can be deployed, the following questions are answered: where are the optimal locations of relay nodes and APs, how is the optimal allocation of sensors to these relay nodes, and what is the hybrid transmission structure of wired-cum-wireless sensor network to minimize the network configuration costs.

The problem is formulated as a Mixed Integer Nonlinear Programming (MINLP) model, which is known to be NP-complete in general. Since powerful solvers such as the Branch-And-Reduce Optimization Navigator (BARON) solve MINLP efficiently, a proper set of test problems from loosely to tightly constrained problem instances is generated and solved using "BARON" (McCarl, 2008; Rosenthal, 2008). The generated problem instances are tested to compare the wireless design against the proposed hybrid design and evaluate the effects of increasing the network lifetime horizon and enlarging the network (number of network nodes) on the proposed design. The performance of the solver is greatly affected by factors including: the number of sensors, available areas for placing relay nodes, and candidate locations for placing APs in the area of deployment.

The remainder of the paper is organized as follows. The related works are discussed in section 2. The notations and mathematical formulation for multi-layer hybrid wired-cum-wireless sensor network design problem is defined in Section 3. The computational results on the generated problem instances are presented in Section 4. Conclusions and future work are presented in Section 5.

2. Related works

The literature is rich with many pieces of research focusing on sensor networks design problems. Energy efficient design is the key challenge for the application of sensor networks because of battery power supply. This section provides a review of available designs that aim to reduce the energy dissipation of the network. Section 2.1 reviews prior work concentrating on a special kind of sensor networks known as hybrid wired-cum-wireless networks. Section 2.2 presents relay location problems for sensor networks.

2.1. Hybrid wired-cum-wireless networks

Designing sensor networks, while considering both longevity and coverage objectives, is a key strategic issue (Akyildiz et al., 2002; Chong and Kumar, 2003). Consequently, multi-tier cluster-based (hierarchical) architectures are proposed in order to minimize the data transmission over long distances, improve routing and connection set up, and maximize the network lifetime (Gupta and Younis, 2003; Wu et al., 2006). Localizing the route set up,