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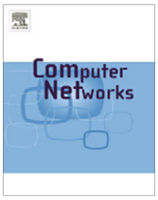

Rate control for heterogeneous wireless sensor networks: Characterization, algorithms and performance

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ABSTRACT

This paper addresses the rate control and resource allocation problem for heterogeneous wireless sensor networks, which consist of diverse node types or modalities such as sensors and actuators, and different tasks or applications. The performance of these applications, either elastic traffic nature (e.g., typical data collection) or inelastic traffic nature (e.g., real-time monitoring and controlling), is modeled as a utility function of the sensor source rate. The traditional rate control approach, which requires the utility function to be strictly concave, is no longer applicable because of the involvement of inelastic traffic. Therefore, we develop a utility framework of rate control for heterogeneous wireless sensor networks with single- and multiple-path routing, and propose utility fair rate control algorithms, that are able to allocate the resources (wireless channel capacity and sensor node energy) efficiently and guarantee the application performance in a utility proportional or max–min fair manner. Furthermore, the optimization and convergence of the algorithm is investigated rigorously as well.

1. Introduction

With the rapid progress of Wireless Sensor Networks (WSNs), the nature of the network is gradually evolving from *homogeneous* toward *heterogeneous* [1,2]. A *heterogeneous* sensor network consists of various types of nodes such as different sensors (e.g., visual, infra-red, acoustic and camera) and actuators (e.g., robots and mobile entities), and coexists of both low-cost lightweight wireless devices (which simply sense the environmental changes) and energy-rich devices (which serve as in-network or multimedia processors). Compared with a *homogeneous* network, it may contain many different applications associated with particular sensors and integrate all the physical information available to provide rich and versatile services. For instance, heterogeneous sensor network opens up new opportunities in healthcare systems. There is a “smart home” for the disabled and the elderly, with temperature, humidity, pressure sensors and camera deployed. It allows care-providers to monitor patients remotely, react timely and offer a better service. In this case, the applications of heterogeneous sensor networks include not only reactive monitoring operations but also proactive controlling actions.

From the data transport perspective, the objective of heterogeneous sensor networks is no longer to solely maximize the sum of data information collected by each sensor.[1] Instead, it is expected to cater for a variety of application performance metrics related to different sensors or sensor modalities. Rate control (also known as flow control) is an important technique of performance assurance in communication networks. The primary objective of rate control is, by regulating the flows, to prevent network

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[1] Hereafter we generally use sensor to refer to all types of sensors including actuators, but differentiate the traffic types by their applications.

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congestion with respect to the network capacity. Particularly in wireless sensor networks, there have been numerous proposals (CODA [3], IFRC [4], WRCP [5], RCRT [6]) purely for congestion control. Inspired by the seminal work of Kelly et al. [7], in the past decade, rate control is further adopted to achieve the global network optimality by modeling application performance as a generic utility function over the available bandwidth [8]. Following this model, utility-based rate control has been extensively studied in typical wired networks [9,10], cellular wireless networks [11,12] and ad hoc networks [13,14]. The approach is essentially the same to formulate rate control as an optimization problem and then maximize total utilities under the network bandwidth constraint. Even though this strategy, well known as optimal flow control (OFC), has made a great success in dealing with both congestion control and performance optimization (particularly in proportional fairness), it also possesses serious limitations as outlined in our paper [15,16].

- At current stage, the OFC approach is only suitable for *elastic* traffic, where each application attains a strictly increasing and concave utility function to ensure the feasible optimal solution and convergence of utility maximization process. It cannot deal with congestion control and resource allocation for communication networks like sensor networks where inelastic traffic is commonly engaged.
- In the utility maximization approach, if each user selects different utility function based on its real performance requirement, the OFC approach usually leads to a totally unfair resource allocation for practical use, in particular, an application with a lower demand is conversely allocated with a higher bandwidth.

In this paper, we characterize application performance as a utility function and develop a utility framework of rate control specifically for heterogeneous wireless sensor networks. In order to discriminate different applications regarding different traffic types, hereafter, we relax the utility function conditions, which only require the utility function to be strictly increasing with the data rate, but not necessarily strictly concave. This relaxation has a significant effect on inelastic traffic that is widely existing in sensor networks. Meanwhile, we notice that some models of sensor network simply assume a fixed source rate for sensor node which might not be optimal from a rate control perspective or even not feasible for a given set of resource constraints. Therefore, we study a self-regulating wireless sensor network in which each node is free to adapt its source rate. Then, we design distributed rate control algorithms that allocate source rate among sensor nodes so that the performances of all kinds of sensor nodes are guaranteed. Specifically, we show that the source rate is allocated properly within the sensor networks and that the utility achieved by each node, even not belonging to the same type, is in a proportional or max–min fair manner.

The proposed algorithms target at sensor networks, both with a unique route from each source to a sink and more generally with potentially multiple routes between each sensor node and a sink. The difference is not uncommon in practice due to the availability of a network layer routing protocol [17] that determines unique routes from sources and destinations. Thus, the inclusion of multiple-path scenario is highly desirable from an analytical as well as a practical perspective.

Moreover, unlike traditional wired and wireless networks, sensor networks intrinsically possess some unique characteristics. Energy is a major concern in wireless sensor networks, since the majority of sensor nodes usually have power limited and unreplaceable batteries. We purposely build a power dissipation model and deliberate the energy constraint to make our proposed algorithms energy-aware. It is aimed to guarantee the operational lifetime of sensor networks, which we believe is vitally important.

The rest of the paper is organized as follows: In Section 2, we describe the system models concerning channel capacity constraint and energy constraint. Section 3 discusses the utility framework of rate control for heterogeneous wireless sensor networks. Following that, a utility fair rate control algorithm is designed and developed for single-path network in Section 4 and for multiple-path network in Section 5. Finally, we present the simulation results to evaluate the performances of the proposed algorithms in Section 6 and make conclusions in Section 7.

Notations: Throughout the paper, we use bold lowercase letters $\mathbf{x}, \mathbf{y}, \ldots$ to denote vectors and bold upper-case letters $\mathbf{X}, \mathbf{Y}, \ldots$ to denote matrices. The notations $\mathbb{R}^D, \mathbb{R}^D_+$ denote the D-dimensional real and non-negative Euclidean spaces, respectively. Generally, we use the calligraphic font $\mathcal{Z}$ to refer to a set, and the cardinality (i.e., the number of elements) of a finite set $\mathcal{Z}$ is denoted by $|\mathcal{Z}|$.

2. System characterization and modeling

Consider a wireless sensor network that consists of a set $\mathcal{S} = \{1, 2, \ldots, S\}$ of sensor nodes and a single destination node indexed by 0 as sink. In total, there are $K = S + 1$ nodes. Each sensor node s is the source that senses and delivers data information to the sink, possibly over multiple hops. It attains a non-negative utility $U_s(x_s)$ for a source rate $x_s \in [m_s, M_s]$ where m_s and M_s are the minimum and maximum source rate requirements of node s respectively. The utility function $U_s(x_s) : \mathbb{R}_+ \mapsto \mathbb{R}$ is assumed to be continuous, strictly increasing and bounded (not necessarily concave), which indicates the performance of node s. Without loss of generality, it can be assumed that $U_s(x_s) = 0$ when $x_s < m_s$ and $U_s(x_s) = U_s(M_s)$ when $x_s > M_s$. For matters of scalability, it can be further assumed that $0 \leqslant U_s(x_s) \leqslant 1$ and $U_s(M_s) = 1$.

To take account of the network with possible multiple path routing, we assume each sensor node s has n_s available routes or paths[2] from the source to the destination. The total number of paths is $N = n_1 + n_2 + \cdots + n_S$.

Denote the $K \times 1$ vector $\mathbf{r}_{s,i}$ the set of nodes traversed by the path $i \in \{1, 2, \ldots, n_s\}$ originated from node $s \in \mathcal{S}$. Let $y_{s,i}$ be the path rate of sensor node s on path $\mathbf{r}_{s,i}$, and

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[2] In the remainder of this paper we will use the terms route and path interchangeably.