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Temporal-aware rate allocation in mission-oriented WSNs with sum-rate demand guarantee

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ABSTRACT

Conventional resource allocation schemes for single-purpose WSNs are unable to capture the dynamicity of network and/or application specifications. This compels us to design mechanisms that support multi-purpose mission-oriented WSNs, where several missions with different characteristics coexist in an integrated WSN. The paper aims to propose an efficient temporal-aware resource allocation mechanism for mission-oriented WSNs. Furthermore, our design supports minimum sum-rate demand guarantee for active sessions of each mission. We use contention graph notion to analytically model the interference in our underlying WSN. Moreover, in-network processing operators play important role in our design scheme. Using a time-variant mission-oriented WSN model, we formulate our resource allocation problem as a *dynamic network utility maximization* problem, which aims to maximize a hybrid mix of an aggregated objective function of missions' utilities and energy consumption, considering capacity, interference and sum-rate demand constraints. Finally, using dual decomposition method, we solve the problem and propose a distributed temporal-aware algorithm called TARC-SD that optimally allocates the shared bandwidth to the sources. The conducted experiments indicate that the TARC-SD algorithm achieves higher network utilization and wider feasible scenarios compared to conventional time-invariant schemes.

1. Introduction

Nowadays, low-cost, low-power, and multifunctional sensors with small size and comprehensive functionality have made the measurement easier and more accurate [1]. Traditionally, sensor nodes of a WSN suffer from the scarcity of resources such as energy, memory, processing power, and wireless bandwidth. Plenty of researches have been conducted to improve the usage of these vital resources via either layered or cross-layer design schemes [2–5]. Many different kinds of applications have been mentioned for WSNs such as monitoring applications, hazardous environment exploration, and seismic sensing [6–8].

1.1. Mission-oriented WSNs

Some of WSN's applications run for long, and some do not. For example, an earthquake monitoring application may continuously monitor seismic activities for a long time. On the contrary, a surveillance application that employs different types of sensors such as video, motion detector, and thermal sensors, may periodically query a subset of these sensors at specific time intervals. In some cases, namely the *mission-oriented* WSNs, several missions with different lifetimes exist in a same system simultaneously [9–11]. By missions, we mean the applications with relatively short active duration which mostly could be found in bandwidth-intensive streaming scenarios such as video sensors, acoustic arrays, and short-range radar feeds [9].

As an example, suppose a set of load sensors and a set of sound detection sensors have been deployed in the battlefield by which we can trace a mobile object and detect suspicious activities, respectively. For a unit which is crossing that location, deciding whether or not to engage an approaching enemy heavily depends on the type of enemy's armament. By fusing the information from these sets of sensors, we can approximately determine that whether the moving object is an armored vehicle or just a reconnaissance military light utility vehicle.[1] When the unit leaves the

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[1] By examining its weight and its engine sound.

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location, that information is no longer needed and the mission's resources can be freed up. How to allocate the network resources to such missions is the matter of concern in this study.

Compared to the conventional single-purpose WSNs, mission-oriented WSNs are characterized by their more stringent Quality of Service (QoS) requirements. In particular, data streams received by each mission should meet a certain quality. For instance, a low quality video stream may practically be useless. Thus, in an appropriate resource allocation scheme, it is so important to guarantee the minimum required resources for each mission, if possible.

1.2. In-network processing in WSNs

It is well known that the radio module usually consumes more energy compared to the processing module [12], so in-network processing has been widely studied in the literature. The basic idea behind the in-network processing is that processing the data in middle nodes can decrease the amount of transmitted data, so there will be a considerable energy saving and more efficient bandwidth utilization [13–15]. Some of in-network processing approaches such as data aggregation or data fusion may even improve the accuracy of the collected data or reduce uncorrelated noise [14]. Usually, the node that performs the process is called the *operator*. Some studies model the behavior of aggregation or fusion operators as a compression operator by simply assuming that the operator output to input ratio is a positive value that is less than 1 [9].

1.3. Dynamic network utility maximization

In the recent years, Network Utility Maximization (NUM) has been used as a promising framework to analytically model the wired and wireless network resource allocation problems. Using a fixed set of sources and predetermined paths in a static network topology, the basic version of NUM [16] concerns with maximizing the aggregate utility of users by allocating optimal rates, while satisfying the capacity constraints.

In mission-oriented WSNs, temporal variation is emanated from mission characteristics. For instance, each mission may be active/inactive in each period. In addition, link capacities may vary due to the environmental noises. Since basic NUM assumes a static model, it cannot capture this dynamic situation. Trivially, NUM can respond to future changes in network characteristics like activation and deactivation of missions by reallocating optimal rates via resolving the new problem.

Recently, *Dynamic Network Utility Maximization* (DNUM) [17] is proposed as a multi-period version of NUM. In DNUM, model parameters and characteristics could vary over pre-specified time intervals. Moreover, a time-coupling constraint called *delivery contract* is introduced in which certain amount of resources has to be dedicated to a flow within some time intervals in order to meet QoS constraints. Similarly, to support QoS requirement of mission-oriented WSNs, each mission can request a minimum sum-rate demand in specified intervals using delivery contracts.

1.4. Paper contribution

The main goal of this paper is to provide an efficient temporal-aware resource allocation scheme under sum-rate demand requirement for mission-oriented WSNs. The main motivation is that characteristics of missions may change over time. As conventional mechanisms are unable to capture the time-varying system model, they fail to address this important requirement. In the light of this motivation and based on aforementioned state-of-the-art DNUM framework, we build our system model in such a way that almost all of the system characteristics can be time-varying.

The in-network processing, energy consumption, and QoS are incorporated in our model as they are among the main properties of the most WSN models. We employ an interference-limited wireless model using the well-known contention graph idea [2]. In our model, the contention graph changes due to the status of missions (active/inactive) at each period. We use contention graph in such a way that there would be no need to store a separate contention graph for each period. In addition, we contemplate in-network processing slightly different from the previous studies so that for each operator the (possibly time-varying) output to input ratio for each of its inputs can be determined separately. To capture the effect of the operators, we redefine the conventional routing matrix notation.

To provide QoS for missions, we attach sum-rate demand constraints to allow each mission to declare its aggregate rate demand. By this constraint, we can exactly specify that a mission should receive at least what amount of information at predetermined interval(s), so our model can be interpreted as a *starvation-free* model. Finally, in addition to shared limited bandwidth that is the main concern of our problem, energy consumption is also considered in our WSN model. In this study, energy consumption is augmented in optimization problem as a subtractive term for the system utility to play its role as a penalty function.

Based on the above considerations, we aim to propose an energy-, temporal-, and in-network processing-aware optimization framework to allocate the proper data rate for the flows to maximize the network-wide mission utilities. Our main contributions toward this endeavor are summarized as follows:

- We formulate a convex program with the goal of optimal rate allocation so as to maximize the aggregated missions' utilities subject to the capacity, scheduling, and rate demand constraints.
- Due to the convexity of our proposed problem and thanks to the mature dual-based approaches, we solve the problem in an iterative distributed manner. Then, we develop a rate control algorithm called TARC-SD that solves the problem granted the knowledge of parameters for the entire time horizon in advance.
- Then, the convergence of the proposed algorithm is proved analytically. We also investigate the practical and implementation issues of the proposed solution in real scenarios. Moreover, we discuss the overhead of our solution.
- Finally, through a set of representative randomly generated WSN scenarios we examine our solution. Experimental results justify the efficacy of TARC-SD algorithm to gain higher system utility and wider feasible scenarios in comparison with the conventional time-invariant NUM-based rate control scheme.

The rest of the paper is organized as follows. Section 2 glances through some of the previous work. Section 3 introduces the system model. The problem formulation is presented in Section 4. Then, we explain the solution in Section 5. Section 6 is dedicated to a discussion about the practicality and implementation issues of the solution. The experimental results are mentioned in Section 7. Finally, the Section 8 concludes the paper.

2. Related works

Network Utility Maximization (NUM) [16,18] framework is among the most promising approaches which have been proposed to improve resource allocation in networking scenarios. The NUM framework has been used in many research areas such as congestion control, flow control, routing, scheduling, and cross-layer designs. An overview of several NUM-based resource allocation approaches can be found in excellent work of Chiang et al. [4].