



A dynamic programming approach: Improving the performance of wireless networks

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ABSTRACT

Traditional wireless networks focus on transparent data transmission where the data are processed at either the source or destination nodes. In contrast, the proposed approach aims at distributing data processing among the nodes in the network thus providing a higher processing capability than a single device. Moreover, energy consumption is balanced in the proposed scheme since the energy intensive processing will be distributed among the nodes. The performance of a wireless network is dependent on a number of factors including the available energy, energy-efficiency, data processing delay, transmission delay, routing decisions, security architecture etc. Typical existing distributed processing schemes have a fixed node or node type assigned to the processing at the design phase, for example a cluster head in wireless sensor networks aggregating the data. In contrast, the proposed approach aims to virtualize the processing, energy, and communication resources of the entire heterogeneous network and dynamically distribute processing steps along the communication path while optimizing performance. Moreover, the security of the communication is considered an important factor in the decision to either process or forward the data. Overall, the proposed scheme creates a wireless “computing cloud” where the processing tasks are dynamically assigned to the nodes using the Dynamic Programming (DP) methodology. The processing and transmission decisions are analytically derived from network models in order to optimize the utilization of the network resources including: available energy, processing capacity, security overhead, bandwidth etc. The proposed DP-based scheme is mathematically derived thus guaranteeing performance. Moreover, the scheme is verified through network simulations.

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1. Introduction

Wireless networks have many military and civilian applications including battlefield surveillance, border and fire monitoring, traffic control, and healthcare and body sensor networks. Designing a durable sensor network has always been a challenge due to the limited energy available in battery-operated devices. Moreover, in sensor networks a typical application has to extract information from the raw data. Typically, the information extraction is tasked to the sink node in order to conserve the energy of sensors. However, sensor devices are equipped with ever more capable processors. Additionally, the amount of extracted information is typically much smaller than the amount of raw sensor data. The energy consumption and the communication delay are proportional to the amount of transmitted data. Hence, the network-wide energy consumption and end-to-end delay can potentially be reduced when the data are processed early at the routing path. The pro-

posed cross-layer optimization will dynamically optimize the performance of the networks in different areas: network routing [20], avoiding energy holes [8], prolonging network lifetime [15] and others.

A number of related algorithms have been proposed for different application environments. In hierarchical-based algorithms [17,9], nodes are partitioned into different levels such that sensing data is transferred from lower to higher, up to the users. In wireless sensor networks, applications will have different requirements for the data collection and dissemination process. For example, a network metric can be short packet delay for time-critical applications. In contrast, better energy utilization is preferred in case of battery operated, long-term monitoring applications. Hence, it is essential that communication protocols are aware of application demands and adopt themselves according to application requirements. The aim of the proposed model is the integration of application requirements in terms of delay associated, security overhead, energy consumption and nodes' capabilities and the design of a communication protocol for better functioning of the network in terms of user requirements.

The proposed scheme improves the performance of the network by distributing the load within the network similar to

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cloud computing methodology. Cloud computing cost-analysis is utilization-oriented and adapts to changing application demand, topology, and resource availability. In a traditional computing cloud, multiple applications are hosted on a common set of servers, which allows the consolidation of application workloads on a smaller number of servers for better utilization. The clouds virtualize resources for example using virtual machines (VM) in order to efficiently distribute and quickly process multiple user requests. For example, a user starts a processing-intensive image manipulation application. Instead of spending hours on a local desktop or transferring to a specific super-computer, the application is inserted into a VM and sent to the cloud to be executed. The user's VM is dynamically assigned and if necessary distributed on physical machines inside the cluster without the user's intervention or awareness [1]. The computing cloud is capable of efficient load balancing and optimization of delay and energy-efficiency beyond what a manual operation would accomplish.

A task scheduling problem in the case of cloud computing deals with meeting users' job QoS requirements and using cloud resources effectively in an economic manner. However, nodes in decentralized wireless networks have to collaborate among themselves to broadcast requests and route data. For example, typical battery-operated sensor nodes have a limited energy supply that limits their lifetime. Hence, such a network has to optimize the available resources in order to increase its lifetime, energy-efficiency, response time, etc. The proposed approach employs the concept of virtualization of resources and virtual machines (VMs) to manage the processing tasks. However, in contrast to traditional, wired computing clouds the wireless variant requires consideration also for communication costs and overhead. The mobile VM calculates the percentage of the task to be completed at a particular node based on the resources available in the network. This methodology applied to sensor networks manages the distribution of tasks among the mobile nodes while reducing the transmission and processing oriented costs including energy and delay metrics. For example, a node can make a decision to either

- Execute the entire set of tasks by itself and relay the final result (typically smaller than the input data set).
- Perform some tasks and transfer partial results to the next available neighbor for further processing, or
- Only transfer the data (and tasks) to the next node.

The proposed scheme also examines how a security overhead impacts the performance of the network in terms of energy efficiency, end-to-end delay, task distribution, network lifetime, etc. In order to minimize the security overhead an MKE [14] scheme is adopted for security. The MKE thwarts CPA attacks in wireless networks while reducing energy consumption. Overall, the proposed scheme aims to improve the performance of wireless network considering various metrics that impact the performance.

The proposed scheme is studied with respect to various cost optimization metrics using either single or multiple metrics. For example, focusing on equal energy consumption distribution will affect the delay associated with the processing of a task and vice versa. The scheme is also analyzed in terms of various routing patterns of heterogeneous nodes and mobile nodes in the network.

In this paper, a mathematical model based on dynamic programming [2] is used to solve the issue of multi-stage decision-making. The decision to perform the task at a particular stage or node of the network depends on various factors as described. Using DP methodology the multi stage decision problem is translated to multiple single stage problems that are correlative and solved accordingly.

2. Background and related work

Optimization of a multi-hop wireless network is most naturally approached using dynamic programming (DP) methodology. Many researchers used the DP methodology in networks to solve various problems including finding optimal routing strategies, minimal energy consumption, optimal strategy in data aggregation, hierarchical routing issues, etc. A DP based scheme routing algorithm with minimal energy consumption has been proposed by Yang [18]. However, designing a minimal energy consumption routing has not been considered. Ciancio and Ortega [4] consider the optimal strategy sequence of data aggregation using the DP principle to get a balance between energy consumption and data distortion. Using the DP principle hierarchical routing is addressed in [3,10].

A dynamic programming optimization method was used in [13] to obtain an optimal scheduling policy that explores the channel dynamics to obtain a reasonable tradeoff between the communication throughput and packet transmission delay. A general DP framework was presented in [11] to obtain the optimal power and rate control policies that satisfy deadline-based QoS constraints. The DP approach was used in [7] to find a smart policy for energy-efficient tracking in wireless sensor networks. Based on the DP approach, an algorithm was proposed [19] for a data-collecting sensor network, where the energy consumed includes both the transmission energy and energy consumed in the electronic circuitry.

A new metric-based cost function model is proposed to improve the performance of the sensor networks using the DP principle. The DP solution yields distributed decision making at each node that minimizes the total cost function. De Couto et al. [5] implemented a routing protocol that incorporates a metric called 'expected transmission cost' which measures the expected number of transmissions required to successfully send a packet across a link. To optimize the end-to-end delay and path capacity, Draves et al. [6] defined a two-term metric called the 'weighted cumulative expected transmission time'. The first term accounts for end-to-end delay while the other accounts for interference. Iannone et al. [12] defined the cost of a link as the inverse of its nominal rate, and showed that by finding low-cost paths.

The dynamic programming technique is used for finding the optimal route in wireless networks for reducing congestion, improving energy efficiency and for a variety of reasons. For example, Zhou [22] used the DP methodology to find optimal routes in an energy efficient manner. However, the principle is not based on the cost function which has been used in the proposed scheme. It is more focused on considering nodes as states of the system, which rather simplifies than holistically solves the network performance optimization challenge. Similarly, Lingyang [16] using DP methodology to determine the best packet forwarding route that has the maximum successful transmission rate subject to the source-to-destination energy consumption constraint. It focuses only on the energy consumption constraint but neglects other contributing metrics to improve the performance of the network.

Using DP methodology many researchers aimed at finding optimal solutions for the network with respect to various metrics, for example the length of routing path, security overhead, energy consumption, end-to-end delay, and throughput. The schemes improve the performance of the network with respect to only individual metrics. However, network performance depends on multiple metrics and it is essential to consider a combined approach. In this paper, a DP based approach is defined which improves the performance of the network in terms of energy utilization, balanced energy consumption in the network, reducing transmission costs and end-to-end delay. Moreover, the proposed scheme enables the optimization of application-layer processing along the routing path which is lacking in the existing literature.

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