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Analytical performance of soft clustering protocols

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ABSTRACT

The success of a mobile ad hoc network (MANET) is strongly related to the protocol used at the medium access control (MAC) layer. Depending on the requirements and the specific network under concern, the protocol parameters at the MAC layer can be arbitrated to make best use of the channel resources. Typically, extensive simulation studies are used to find the best values for these variables. The problem with this approach is the need for excessive amounts of processing power and time. As the dimensions of the decision space increase, the need for processing power grows exponentially. This paper addresses this problem by developing an analytical model that reflects the relationships between protocol parameters and the overall performance of the protocol under various network conditions. Specifically, we model the MH-TRACE cluster-based protocol, which is capable of supporting real-time data transmission. The model is capable of estimating performance measures such as energy consumption and number of receptions while being simple enough to be run for a large set of parameters. The model can be used to optimize parameters of the protocol (such as the number of frames per superframe) as well as to predict the performance variations as the external conditions (such as data generation rate) vary.

1. Introduction

In wireless communications, the goal of the medium access control (MAC) protocol is to efficiently utilize the wireless medium, which is a limited resource. The effective use of the channel strongly determines the ability of the network to meet application requirements such as quality of service (QoS), energy dissipation, fairness, stability, and robustness [1,2].

Based on the collaboration level, MAC protocols can be classified into two categories: coordinated and non-coordinated. In non-coordinated MAC protocols, nodes contend with each other. IEEE 802.11 is an example of non-coordinated protocols. Non-coordinated protocols are generally better suited for networks with low data rates. On the other hand, in coordinated channel access protocols, there are regulating devices that determine how the medium is shared. IEEE 802.15.3 [3], IEEE 802.15.4 and MH-TRACE [4] are examples of such coordinated protocols. In general, coordinated access protocols are better suited for networks where the load is high. Also, coordinated channel access schemes provide support for QoS, reduce energy dissipation and increase throughput for low-to-mid noise levels and for dense networks [5].

IEEE 802.15.3, IEEE 802.15.4 and MH-TRACE all manage the multiple access scheme through a TDMA structure, as this approach has been shown to provide satisfactory performance in terms of QoS and energy dissipation. MH-TRACE further uses a soft clustering approach where the clustering mechanism is utilized only for providing channel access to the member nodes. Hence, each node is capable of communicating directly with every other node provided that they are within communication range of each other. IEEE 802.15.3 and IEEE 802.15.4 only allow communication among the members of distinct clusters

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(piconets) in their peer to peer mode, while in star topology mode, nodes in distinct clusters can only communicate through their piconet controllers.

It is important not only to choose the correct protocol but also to adjust the parameters in accordance with the application requirements. Many of the parameters in cluster-based protocols are set a-priori based on estimates of network conditions and based on a specific physical layer. The true relationship between the parameters and the protocol performance can only be determined by analysis. Although simulation studies reveal the performance of a protocol for a certain set of conditions, the statistical accuracy of the simulation results is questionable unless repeated extensively. For large and dense networks, this approach requires excessive amounts of processing power. Moreover, results obtained from those studies are only valid for the selected parameters and do not reveal the full impact of these parameters on the performance of the protocol.

In order to address this problem, we have developed an analytical model that reflects the relationships between the protocol parameters and the overall performance of the protocol under different network conditions for a TDMA-based clustered protocol, MH-TRACE. Specifically, we develop a model that relates the TDMA frame parameters (number of slots per frame and number of frames per superframe) and the node density to the expected number of dropped packets and the expected number of collisions. This model enables us to find the set of parameters that maximize overall throughput or energy efficiency for TDMA-based clustered protocols such as IEEE 802.15.3 (peer to peer mode), IEEE 802.15.4 (peer to peer mode) and MH-TRACE. We use this model to analyze the MH-TRACE protocol.

This paper is organized as follows. In Section 2, we discuss related work. The scope of the paper is introduced in Section 3, together with a short description of the MH-TRACE protocol. An analytical model that estimates the performance of soft clustering protocols for a given set of parameters is presented in Section 4. Section 5 discusses the validity of the analytical model by comparing the analytical results with those found via simulations for MH-TRACE. Using the analytical model, the degree of spatial reuse present in a network utilizing the MH-TRACE protocol is optimized for both maximum throughput and minimum energy consumption per generated packet in Section 6. In Section 7, the performance of the protocol is investigated as the transmission power and the data source model is varied. Section 8 concludes the paper with final comments.

2. Related work

Various analytical studies of protocol performance exist in the literature. These studies range from detailed protocol specific models to more general models that can be applied to a group of protocols.

One line of research is focused on more generalized analysis that covers a set of protocols that share a certain property. These studies use more generalized assumptions and focus on certain descriptive performance metrics rather than trying to model details of a certain protocol. For example, the authors in [6–8] study the optimal size of a cluster for cluster based data aggregation schemes without going into the protocol dependent parameters. Studies on the delay and the throughput characteristics of TDMA/CDMA MAC protocols, such as those described in [9,10], also fall under this category.

Protocol specific studies approximate the protocols under concern in detail using protocol dependent assumptions. IEEE 802.11 is one of the most extensively studied protocols. Bianchi [11] present a simple analytical model to compute the saturation throughput performance of the IEEE 802.11 Distributed Coordination Function. Later on, more detailed studies on IEEE 802.11 have been proposed, based on the protocol and its extensions [12–14] such as IEEE 802.11e, which has several quality of service (QoS) enabling features to support real-time traffic.

Being one of the most widely used network types, GSM networks have also attracted considerable attention, with most of these works analytically deriving the performance of GSM networks. For example, in [15], a model for cell dimensioning and performance evaluation is presented.

IEEE 802.15.4 is another widely studied protocol. The very first analytical study of IEEE 802.15.4 was described in [16] in the context of medical sensor body area networks. Various other papers [17–20] have been published since then, having different sets of assumptions and different operation modes of the protocol. For instance, in [17] the analysis is focused on the star topology, while in [18], a peer to peer beacon-enabled cluster-tree structure is considered. Similar analytical studies for IEEE 802.15.3 can be found in the literature, such as the ones in [21,22].

Our work lies in between those approaches for analyzing protocol performance. Even though we focus on a specific cluster based MAC protocol utilizing soft-clustering, namely MH-TRACE, the assumptions used in the analysis make the generalization of the model to other MAC protocols that employ a TDMA structure possible.

3. Background

In this section, we define the scope of the paper. We discuss the basics of clustering approaches and their interaction with the other layers of the communication stack. We also provide an overview of the MH-TRACE protocol.

3.1. Clustering approaches

Regardless of the partitioning scheme, the main consideration in forming clusters is the load distribution in the network. Clusters should be formed in such a way that they are able to meet the demand for channel access of the nodes in the cluster as much as possible. When the cluster is not able to meet the demand, either some of the transmissions are deferred (better suited for guaranteed delivery traffic) or the packets are dropped (better suited for best effort traffic). Thus, while designing a protocol or determining the performance of a specific protocol, the load distribution has crucial importance. Clustering approaches may be classified as soft and hard clustering. In