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A general model for MAC protocol selection in wireless sensor networks

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ABSTRACT

Wireless sensor networks (WSNs) have become relatively common in recent years with application scenarios ranging from low-traffic soil condition sensing to high-traffic video surveillance networks. Each of these applications has its own specific structure, goals, and requirements. Medium access control (MAC) protocols play a significant role in WSNs and should be tuned to the particular application. However, there is no general model that can aid in the selection and tuning of MAC protocols for different applications, imposing a heavy burden on the design engineers of these networks. Having a precise analytical model for each MAC protocol, on the other hand, is almost impossible. Using the intuition that protocols in the same behavioral set perform similarly, our goal in this paper is to introduce a general model that can help select the protocol(s) that satisfy given requirements from a protocol set that performs best for a given context. We define the Combined Performance Function (CPF) to demonstrate the performance of different category protocols for different contexts. Having developed the general model, we then discuss the models scalability in terms of adding new protocols, categories, requirements, and performance criteria. Considering energy consumption and delay as the initial performance criteria of the model, we focus on deriving mathematical models for them. Previous rules of thumb for selecting MAC protocols support the results extracted from CPF, providing a practical verification for our model. We further validate our models with the help of simulation studies.

1. Introduction

Unique characteristics of wireless sensor networks (WSNs), in addition to being mostly application-specific, make traditional network algorithms and protocols unsuitable for them. Specifically: (i) wireless sensor nodes usually have limited resources such as available energy, storage, computation and communication capabilities; (ii) the amount of data transmitted is typically lower than in other networks (e.g., Wi-Fi); and (iii) wireless links are unreliable by nature, with an additional caveat that nodes usually spend a considerable amount of time in a sleep state, saving energy. We also note that the characteristics of sensor networks may be different in different contexts. For example, small sensor networks used in farming have fewer nodes with more resources [1]; traffic load may be significantly higher in multimedia sensor networks [2]; links are more unreliable in underwater sensor networks [3]; whereas at the other extreme, in some WSNs (e.g. the floating sensors project [4]), cell phones are used as sensor nodes and the cellular network provides a centralized infrastructure for communication.

In most WSNs, the medium access control (MAC) sublayer provides mechanisms and policies for sharing the

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wireless medium. Clearly, not all MAC protocols are well suited for every situation. MAC protocols for WSNs can be classified in several ways. Some survey articles [5–7] have focused on traditional taxonomy, i.e., contention-based and reservation-based approaches. However, these classifications do not take the application context of individual sensor networks into account, and hence provide only limited insights. The authors in [8] classify MAC protocols based on their behavior and claim that each category is useful for a different traffic load. Similar behavioral categorization is depicted in [9] by showing the evolution of MAC protocols for wireless sensor networks over the years of 2002–2011.

During the design but before the deployment of a WSN, an important question needs to be answered: which MAC protocol is better for the given application scenario? Since there is a lack of unified analytical models addressing the behavior of MAC protocols under different conditions, it is hard to address this question satisfactorily. Thus, most decisions are made based on questionable "rule of thumb" engineering principles. (For example, the most common rule of thumb is to employ preamble sampling protocols in low-traffic environments, common active period protocols for medium traffic situations, and scheduled protocols for high-traffic loads.) It could be claimed that using such rules of thumb is enough for making a decision but Example 1 presents two application scenarios that will help us show how difficult such a task may be.

Example 1. Suppose we are looking for a MAC protocol for an environment-monitoring application with the specifications and the network characteristics mentioned in Table 2 (except for the number of nodes, network radius, and packet generation rate). For security reasons, the MAC protocol should prevent overhearing; moreover as the network topology may be unknown we are looking for a distributed protocol. Based on the application, energy consumption is a main concern; however the delay should also be reasonable. Consider the following two scenarios. In the first scenario there are 90 nodes distributed uniformly in a field with the radius of 100 and the average network packet generation rate of 100 packets per second. The network in the second scenario contains 110 nodes and the network radius is 70.

We will show in Section 2.1 that even slight changes may greatly affect the performance of MAC protocols. For each scenario in Example 1, we will also select a MAC protocol based our current protocol pool and the model we propose in this paper.

The number of proposed MAC protocols for WSNs is large (and still rising); this, in addition to the complexity of some of these protocols, makes it almost impossible to obtain a precise analysis for each one of them. Intuitively, the protocols in the same behaviorally-similar set should have similar performance characteristics. Therefore, if we can decide which set is better for a given situation, we can use a qualitative comparison to find the best match. Using this intuitive assumption, we introduce a general model for selecting MAC protocols for wireless sensor networks. We attempt to make the model scalable as well, so that new sets, protocols, requirements, and performance criteria can be added to it gradually.

Our contributions are summarized as follows:

- The main contribution of the paper is the introduction of a general model for selecting MAC protocols for wireless sensor networks for different network specifications and protocol settings, requirements, and performance criteria importance/cost functions. Our model helps finding the protocol that satisfies the requirements, from the set that performs best for a given situation.
- We define the Combined Performance Function to compound performance analyses under different criteria.
- We show how new protocols, sets, and requirements can be added to the model, making our model future proof.
- Focusing on performance analysis, we consider energy consumption and end-to-end delay as the initial performance criteria, and derive the mathematical performance model for the three categories of MAC protocols mentioned in [8].

We will show in Section 2.1 that the rules of thumb strongly correlate with the findings based on our model. We also validate our models by performing detailed simulation studies. The initial version of our model with a web user interface is accessible online [10].

The rest of the paper is organized as follows. The general model is presented in Section 2, including the Combined Performance Function (CPF) and the description of model expendability. Section 3 develops energy consumption models used in our analyses. Approximate delay models are derived in Section 4. Section 2.1 presents the CPF incorporating the previous two models. Simulation results are presented in Section 6 to validate our models. Related works are briefly discussed in Section 7. Finally, conclusions are drawn in Section 8.

2. General model

In this section we present our general model for MAC protocol selection. The intuitive assumption behind our model is that if MAC protocols are behaviorally clustered, the protocols in the same category should have similar performance characteristics. Using the categorization presented in [8], Table 1 presents a qualitative comparison between the MAC protocols of different categories, listing major behavioral characteristics that affect their performance. Although Table 1 does not provide the numerical values, it indicates that protocols in the same category have similar characteristics. For example, DMAC [11] is an extension over TMAC [12] (which in turn is an extension on SMAC [13]) that defines a duty cycling chain in order to be tailored to data gathering trees in WSNs. Even though DMAC is not a direct extension of SMAC, looking at Table 1, some may notice that the basic properties of SMAC are still reflected in it. If a protocol is not similar to any of the protocols in any of the categories, it should be separately analyzed; this is further explained in Section 2.2.

Algorithm 1 presents our MAC protocol selection framework for a given context (ξ represents the network specifications and protocols settings, R represents application requirements, and κ is used for importance/cost coefficients – cf. Section 2.1). The algorithm helps determine the categories that have at least one protocol that satisfies the