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Automated design algorithms for tactical wireless networks

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ABSTRACT

To guide users who attempt to deploy wireless networks in military applications, there is an evolving need for developing systematic methodologies to analyze/predict the performance of mobile ad hoc networks (MANETs). In addition, the advance in cognitive networking research provides opportunities for exploiting unused spectrum to optimize throughput of MANETs. However, with the increasing number of parameters/constraints, there is even a more demanding need to develop automated methodologies to design/tune such networks.

In this work, we study the concepts and challenges for automatic design/re-configuration of cognitive MANETs, in addition to proposing design automation algorithms. The paper is divided into two parts. In the first part, we describe the design objectives, imposed constraints, and involved parameters in MANET design. We discuss how cognitive techniques can be employed to exploit the unused spectrum in military architectures. We then discuss the challenges that face the design/re-configuration of a cognitive network and their implications at different network layers. We also describe possible implementation options for designing MANETs that employ cognitive features at all layers. In the second part of this work, we propose design automation algorithms for optimally setting parameters to achieve a desired objective and satisfy certain constraints. Despite providing the optimal configuration, the simple approach of testing all possible combinations of parameter settings has significant time complexity (the COMB approach). Thus, we propose a novel heuristic (Sequential Parameter Optimization or SEPO) for searching through the possible parameter settings and selecting the best design options. SEPO is efficient in terms of both convergence speed and parameter tuning. We also discuss the foundation for using supervised learning to speed up the design (search) process. By evaluating realistic design of military-like scenarios that require optimizing a diverse set of metrics, we show that SEPO generates comparable results to the optimal, straightforward (slow-converging) COMB approach that is based on exhaustive search.

1. Introduction

Efficient design of mobile ad hoc networks (MANETs) for Future Force networks is a primary objective for both the military and the commercial sectors. Networking of wireless devices in the battlefield is critical to ensure the continuous and timely flow of information that contributes to the success of a mission. Commercial applications also benefit from efficient methodologies and tools for designing MANETs for applications, such as video conferencing and online gaming. Efficient application design ensures that quality service is provided to ensure user satisfaction and fair pricing.

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MANET applications have been limited by the lack of methodologies or tools that analyze and re-configure the design of the network over the duration of a mission (for military purposes) or application (for commercial use). There is a critical need for intelligent design of tactical networks prior to deployment in order to prevent loss of lives and avoid usage of expensive resources. Military applications use a network model that is different from commercial applications [1,2]. In military applications, there is no fixed infrastructure and the network is typically structured into multiple tiers/subnets (hierarchy). One challenge in designing tactical networks lies in the difficulty to determine which parameters to tune and how applicable such tuning is in field deployments. Another challenge is how to design algorithms that would search through the huge domain of parameters that may belong to different functions/layers of the network. These algorithms should guide the network designer to set the network parameters based on the foreseen performance trade-offs.

Currently, network simulation tools evaluate the expected performance of networks under user-defined conditions or scenarios. The available network simulation tools (e.g., NS-2 [10], OPNET [11], and QualNet [12]) are capable of taking as input the traffic pattern (operational scenario) and a set of network parameters/settings (e.g., routing algorithms, MAC protocols, etc.). They use these inputs to run traffic in the proposed network and characterize its performance. These tools provide very realistic network models and protocol implementations. However, their capabilities are focused on the *analysis* of working scenarios and not on the *design* of networks to accommodate expected traffic. Thus, they are not ideal for providing the network designer with guidelines on how to select and tune the network parameters under specific network conditions and traffic load, and while the mission is in progress. Although the user can run all possible sets of parameter options on simulation tools to infer the optimal values, this process is quite tedious and can be extremely slow, especially in large-scale networks. To rapidly provide the user with recommendations on parameter values, we need to study a high level of network abstraction (i.e., analytic models) to mimic protocol performance while skipping the details of slow packet-level simulation. We also need new methods to automate the process of optimizing the network parameters for better user guidance.

In our previous work [3–5], we have set the foundation needed for moving toward automating network design. We have addressed one important challenge in these works and defined the most critical parameters for wireless network design. We have also discussed the time granularity at which automated design can be made to fit military networks.

In this work, we address the other important challenge, which is developing search algorithms that have tractable (i.e., non-exponential) time convergence and also high accuracy (compared to exhaustive/combinatorial search). We also incorporate mechanisms for favoring parameter values over others based on their applicability. Toward this goal, we propose the following algorithms: (1) Common Branch (COMB), which relies on exhaustive search (full factorial experimentation [8]) and serves as a baseline for comparison and (2) Sequential Parameter Optimization (SEPO), which is an efficient algorithm with polynomial-time convergence and high accuracy (fractional factorial experimentation [8]). For these algorithms, we also discuss the time complexities and associated limitations. Finally, we discuss the foundation needed for using supervised learning in speeding up the automated design process.

The rest of this paper is organized as follows. Section 2describes the general concepts of automated design and typical design/optimization parameters. Sections 3–5describe the proposed algorithms, namely, Common Branch, Sequential Parameter Optimization, and Learning-based Design, respectively. Section 6evaluates the proposed algorithms on realistic military scenarios. Finally, Section 8concludes this work and provides directions for future work.

2. Background: Automated Network Design (ADM)

We discuss the desirable objectives and typical constraints that are imposed on MANET design (refer to [3,4]for more details). Then, we focus on the design knobs that a design tool should optimize.

2.1. Design objectives/constraints

We define the design objectives as the metrics that the network designer plans to optimize. Table 1 lists the set of design objectives that the automated design tool supports. These objectives are classified into three categories: application-based, routing-based, or topology-based.

Topology-based objectives are related to how links are formed to connect the network. Link connectivity can also be set to ensure the availability of multiple link-disjoint paths between every pair of nodes in the network. Routing-based objectives are related to how a path is selected between a source node and a destination node. Topology- and routing-based objectives represent the network performance aspects. From the application's perspective, metrics such as loss, throughput, and flow delay are most

Table 1
Optimization categories/objectives.

Category	Objective (Minimization)
Application-based optimization	Traffic loss (total lost bits/total requested load in bits) Flow loss (number of dropped flows/ number of requested flows) Average delay per flow
Routing-based optimization	Average path length Average transmission power/path Energy consumption (nodes/links)
Topology-based optimization	Network diameter Node transmission (Tx) power Diameter & node Tx power Number of domains