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Review article

Fault-tolerant interference-aware topology control in multi-radio multi-channel wireless mesh networks

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ABSTRACT

Wireless Mesh Networks offer an effective technology to establish broadband wireless services. Due to this application, robustness against failures and throughput improvement are the two main objectives in designing such networks. In this paper, we use the "topology control" as a set of tools to reach these objectives. Topology control in wireless mesh networks is an NP-hard problem; therefore, we propose a heuristic method known as Fault-Tolerant Interference-Aware Topology Control (FITC) to solve it in a distributed fashion. In this method, we first guarantee that the network is K-Connected using the graph modification, routing and channel assignment. Then, power control, rate adaptation, channel selection and scheduling is applied to enhance the network throughput. Due to the static channel assignment and the fixed location of the nodes in the network, the first part of the algorithm is conducted using a centralized method, while a distributed cross layer method is applied for the second part. Simulation results validate the efficiency of the proposed method in achieving the main objectives.

1. Introduction

Wireless Mesh Networks (WMNs) are a class of multi-hop networks, which offer a wireless backbone for broadband wireless services such as public access to internet, neighborhood networks, supervisory-security applications, organizational networks and building automation [1]. This network consists of wireless mesh routers, which provides the infrastructure required for traffic transmission between mesh clients and to/from clients out of the mesh network [2].There is no limitation on power consumption neither is there any mobility challenges in wireless mesh networks unlike wireless sensor networks and mobile Ad-hoc networks where power consumption and nodes mobility are the major challenges. As such, we cannot use the algorithms and proposed methods for sensor and mobile ad hoc networks in this type of network. Robustness against failures and maximizing throughput are the two major challenges in wireless mesh networks. In order to increase the network throughput, multi-radio multi-channel technology is introduced in wireless mesh networks [3]. In this technology, each mesh router is equipped with some radio interfaces and there are some non-overlapping frequency channels which can be assigned to the radios. These networks are known as Multi-Radio Multi-Channel WMNs (MR-MC WMNs). The ability to use multiple radios on different channels allow the routers to send/receive packets to/from several neighboring nodes, simultaneously. This feature brings about the efficient use of spectrum and increases the available bandwidth. The effective assignment of channels to radio interfaces can affect the network throughput considerably. In this situation, some nodes have more than one channel to communicate and therefore, selection of proper channel has effects on load balancing and network performance. In this paper, we refer to this problem as *channel selection*, which is different from *channel assignment*.

Due to the limited number of radio interfaces and non-overlapping channels, some links interfere with others and therefore, there is no possibility to concurrent transmission on these links. More nodes are able to transmit simultaneously with more data rates when the transmission power and rate is controlled. Moreover, by using a contention-free MAC protocol based on scheduling and by assigning different time slots to transmissions with co-channel interference, prevention of collision is possible. Therefore, it is essential to use an efficient strategy for resource assignment in order to improve the network throughput. This strat-

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egy includes using the channel assignment, power control, rate adaptation, channel selection, scheduling and path selection.

From the network robustness point of view, failure of one or more nodes can interrupt the connection between some routers, if the requirements are not considered. According to definition, a network is said to be robust against failures if it still remains connected despite the occurrence of disruption in arbitrary K nodes. This property is called *K-Connectivity*. In this case, the loss and delay resulting from nodes failure can be minimized using the proper recovery algorithms.

Unlike in wired networks where topology changes only in the case of node failure, in WMNs there are also other factors which change the topology such as channel assignment and variations in power/rate. Therefore, the tools for controlling power, rate adaptation, channel assignment and channel selection have significant impact on network robustness against failures as well as on its throughput. Although a large amount of study has been conducted on maximizing throughput in wireless mesh networks, most of them assume single radio, single channel networks and a vast majority of them do not consider the robustness of the network against failures. In addition, many researches do not use the power control, rate adaptation, channel assignment/selection, scheduling and routing tools concurrently.

In this paper, we use all of the topology control tools to improve the throughput and load balancing in multi-radio multi-channel wireless mesh networks, while preserving the network robustness against failures. In this manner, we propose a heuristic method known as Fault Tolerant Interference-Aware Topology Control (FITC) for topology control. The proposed algorithm employs the set of available tools, which are power control, rate adaptation, scheduling, routing and channel assignment/selection. In our proposed strategy, the solution is divided into two parts. In the first part, an algorithm called Network Formation and Modification Algorithm (NFMA) is proposed in which its main objective is building a K-Connected network topology, while trying to reduce the potential interference in the network. In the second part, by using the resulted topology from the first part, the objective is maximizing the network throughput along preserving the K-Connectivity feature of the network. The algorithm proposed for the second part is named Throughput Maximization along with preserving K-Connectivity (TMKC).

The rest of the paper is organized as follows. Section 2 reviews the previous works. The details of network model, definitions, assumptions and the problem description is described in section 3. In the fourth section, the proposed method for topology control is presented. Section 5 is dedicated to the simulation results and their analysis. The paper is concluded in section 6.

2. Related works

In recent years, extensive research has been carried out to improve the throughput in wireless mesh networks. In [4], we introduce an iterative algorithm for finding the best multicast tree based on the minimum number of hops between source and destinations by using the rate adaption and channel selection. The proposed strategy enhances the throughput and reduces the co-channel interferences. In this paper, the protocol interference model is employed for simplicity and the transmission power is assumed to be fixed. Conversely, the network robustness against failures and channel assignment is not considered.

In [5], Capone et al. investigated the problem of cross-layer optimization of scheduling along with power control and rate adaptation. They assumed a single radio – single channel network with the specified traffic on the links. In other words, they did not consider the routing and channel assignment problem. As a result of the computational complexity of the proposed problem, the authors presented an alternative formulation in which the decision variables indicated the compatible sets of links with the capability of activation in each time slot. Furthermore, the column generation approach was used to calculate the lower band. The extended problem of resource allocation in [6] propose a comprehensive cross-layer optimization model. Here, in addition to the scheduling along with power control and rate adaptation, the routing and channel assignment are also investigated.

In 2010, Luo et. al. [7] developed two computational tools for joint optimization of rate control, power control, scheduling and routing. Moreover, they studied the relation between frequency reuse and network performance as well as multi-hop benefits against single-hop. The tools developed by Luo et al. are based on column generation and provide a suboptimal solution in acceptable time. In [8], the authors proposed a Mixed-Integer Linear Programming(MILP) model and formulate the problem of gateway nodes selection along with the power control, routing and time slot assignment in order to maximize the service level of nodes. They proposed a heuristic method which comprised two steps in order to solve the problem in a serial manner. In the first step, only the selection of gateways is considered. In the second step, given the fixed number of gateways, the solution of the primary problem is studied. The issues of rate adaptation, channel assignment/selection and network robustness against failures is not considered in this reference.

In [9], Hedayati et. al. first formulate the throughput maximization as an optimization problem. To this end, they exploit the power control and rate adaptation. Since the problem is NP-hard, they suggest a centralized heuristic method. Afterward, they introduced a distributed method in [10]. In these papers, the network is supposed to be a single-radio single-channel and therefore, the issues of channel assignment and its impact on throughput is not considered. Conversely, the traffic on the links is assumed to be known; therefore, routing impact on throughput is not studied. Moreover, the network robustness against failures is not considered.

In [11], the authors proposed algorithms to select a set of nodes in order to establish an infrastructure in ad hoc networks, which are efficient in load distribution and robustness against failures. The authors in [12] investigated the critical node density required to ensure that an arbitrary node in a large-scale wireless multi-hop network is connected (via multi-hop path) to infinitely many other nodes with an arbitrary probability. Power consumption reduction and robustness against failures are the two significant challenges in high scale WSNs discussed in [13]. In this paper, the network architecture is assumed to be cluster-based, where the cluster head receives the information and sends them to the base station. Therefore, failure of the cluster heads poses serious problems. In this manner, the authors proposed a distributed fault- tolerant energy-aware routing method. In [14], different methods of fault tolerant topology management in WSNs are studied. In this paper, due to failure and energy discharge, some applications of WSNs in harsh environments are pointed where there is a possibility of node movement. Therefore, the topology management is supposed to be an essential factor. Moreover, the related works in this area are briefly studied by dividing the methods into two groups of proactive and reactive. The algorithms and methods presented for WSNs and MANETs are not applicable in WMNs, because the main challenges of these networks are the power consumption and nodes movement, which are insignificant in backbone architectures such as WMNs.

In [15], a Multi-Radio Multi-Channel WMN is considered. Given that the primary network is K-Connected; the authors presented an algorithm for channel assignment which reduces the potential interference while preserving the K-Connectivity feature. However, other topology control tools and their impacts on connectivity are