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Impact of multiple channels and radios on the performance of a TDMA based wireless mesh network

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ABSTRACT

In this paper, we theoretically analyze the performance in terms of end-to-end call acceptance in Multi-Channel Multi-Radio (MC-MR) Wireless Mesh Networks (WMNs) using queueing theory techniques. We study the impact of the routing protocol and the channel assignment algorithm on the end-to-end call acceptance and address the issue of providing deterministic QoS guarantees to a designated set of nodes. The significance of our work lies in providing an insight into the bounds of the probability of call acceptance under a given set of parameters for a WMN and provide a framework for comparison of existing routing protocols and channel assignment algorithms. This can be used for network dimensioning and comparative study of different protocols. We have adopted a TDMA-based WMN as our base framework. We consider the case of differentiated class of users and derive upper $\left(P_{Acc}^{Max}\right)$ and lower $\left(P_{Acc}^{Min}\right)$ bounds for the probability of call acceptance (P_{Acc}) and theoretically estimate the probability of system saturation (P_{Sat}) (which is the probability that no more new calls can be accepted in the network). Through simulations, we study the dependence of the (P_{Acc}) on the number of radios in each node $(\mathscr{K})$, the number of channels available in the network (C), the network load (ρ), the routing protocol used, and the channel assignment algorithm. We also study the effect of Weighted Cumulative Expected Transmission Time (WCETT) routing metric and compare its performance with the Shortest Path (SP) routing protocol. The increase in P_{Acc} with the WCETT metric emphasizes the need to consider better routing metrics in an MC-MR network.

1. Introduction

Wireless Mesh Networks (WMNs) have recently gained significant attention, since they address important problems such as growing bandwidth demand along with scarcity of the available spectrum and the need for flexible, easily deployable, self configuring, and adaptable networks. WMNs mix the robustness of cellular networking with the flexibility of ad hoc networking. Emergence of such networks has also been spurred by the development of recent standards such as the IEEE 802.16 [1] and other special working groups such as IEEE 802.11s in the context of IEEE 802.11 networks [2]. WMNs are characterized by an ad hoc backhaul, which is the infrastructure part of the network to which the clients connect. The backhaul, mainly consists of wireless mesh routers that are interconnected in an ad hoc manner. The clients are unaware of the backhaul structure and directly connect to one of the wireless mesh routers.

The main characteristics of fixed WMNs considered here are: (1) There are multiple orthogonal channels of operation available in the network. (2) Mesh nodes are stationary and have multiple radio transceivers, which allow them to communicate simultaneously with more than one neighboring mesh node, using different channels in an interference free manner i.e., a mesh node can be transmitting or receiving in a channel *A* with mesh node *x* while

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simultaneously transmitting or receiving in channel B with mesh node $y(A \neq B)$. (3) Due to the limited number of channels available, channel contention is possible, leading to collisions and interference.

A very important consideration for the widespread deployment of such broadband wireless networks is the support of bandwidth intensive applications such as streaming video and real time voice and video traffic. In order to support such traffic, the network must provide QoS guarantees on the connection. A few of the important aspects to consider while providing such guarantees is the channel assignment algorithm which effectively utilizes and distributes the network resources and the routing protocol which chooses paths that satisfy the QoS requirement. For supporting real time traffic in wireless networks, TDMA based MAC manages the limited resources available and helps in providing QoS guarantees. Many existing works use TDMA based MAC for providing QoS guarantees. A problem of considerable interest is the estimation of theoretical guarantees that can be provided by any QoS scheme. Such estimates give us clarity on the maximum guarantees that can be provided and also act as a reference with which we can compare the performance of existing protocols. Our work provides an insight into the bounds of the probability of call acceptance under a given set of parameters for a WMN and provides a framework for comparison of existing routing protocols and channel assignment algorithms. This can be used for network dimensioning and comparative study of different protocols.

In this work, we analyze the performance in terms of end-to-end call acceptance (which is a measure of the number of calls that can be admitted into the network) of a TDMA-based Multi-Channel Multi-Radio (MC-MR) WMN with multimedia traffic (UDP traffic) in terms of the probability of call acceptance (P_{Acc}). We model the system using a Markov Process Model and study the dependence of P_{Acc} on the number of radios in each node ($\mathscr{K}$), the number of channels available in the network (C), and the network load (ρ). We consider a network with calls belonging to different classes based on which the requirements of the calls are prioritized. The QoS constraint of the calls is that of bandwidth. We derive upper $\left(P_{Acc}^{Max}\right)$ and lower $\left(P_{Acc}^{Min}\right)$ bounds for P_{Acc} and estimate the probability of system saturation (P_{Sat}) which is the probability that no more new calls can be accepted in the network. We also estimate the deterministic guarantee limit which is a measure of the number of high-priority calls that can be admitted into the network. To study the impact of routing on end-to-end call acceptance, we compare the probability of call acceptance for two routing protocols: Shortest Path (SP) routing protocol and the Multi-Radio Link-Quality Source Routing (MR-LQSR) protocol which uses the Weighted Cumulative Expected Transmission Time (WCETT) metric [3].

The rest of the paper is organized as follows: Section 2 summarizes the related work, Section 3 describes the network model, Section 4 contains the derivation of the theoretical bounds, Section 5 discusses the impact of the channel assignment algorithm, number of radios in each node, and the number of channels available in the network on P_{Acc}, Section 6 gives the details of the simulation studies, and Section 7 concludes the paper.

2. Related work

MC-MR multi-hop wireless networks have recently received extensive research attention due to their potential future applications. Several studies have been done on the capacity of Multi-Channel networks in recent times. In [4], the authors analyze a Multi-Channel network where the number of radios m at each node is less than the number of available channels c. The dependence of the capacity on the ratio $\frac{c}{m}$ is studied. It is shown that in the random network case there are three different capacity regions: (1) the per flow capacity being $\frac{W}{\sqrt{n \log n}}$ (where W is the link bandwidth and n is the number of nodes in the network) when $\frac{c}{m} = O(\log n)$, (2) the per flow capacity being $\Theta(W\sqrt{\frac{m}{nc}})$ when $\frac{c}{m} = \Omega(\log n)$ and also $O\left(n\left(\frac{\log\log n}{\log n}\right)^2\right)$, and (3) the per flow capacitybeing $\Theta\left(\frac{Wm \log\log n}{c \log n}\right)$ when $\frac{c}{m} = \Omega\left(n\left(\frac{\log\log n}{\log n}\right)^2\right)$. In [5,6], the capacity and connectivity of Multi-Channel wireless networks with channel switching constraints are considered. In particular, they consider networks where each node is restricted to switch within a set of f channels. Two specific constraint models viz. *adjacent* (c,f) assignment and *random* (c,f) assignment are proposed. In *adjacent* (c,f) channel assignment, a node may switch between f adjacent channels, but the adjacent channel block is randomly assigned. In *random* (c,f) assignment, each node may switch between a pre-assigned random subset of f channels. For the *adjacent* (c,f) assignment case it is shown that when $c = O(\log n)$ the capacity scales as $\Theta\left(W\sqrt{\frac{f}{cn\log n}}\right)$. For the *random* (c,f) assignment case it is initially shown in [5] that the capacity is $O\left(W\sqrt{\frac{p_{rnd}}{n\log n}}\right)$ and also $\Omega\left(W\sqrt{\frac{f}{cn\log n}}\right)$ and later in [6] shown to be $\Theta\left(W\sqrt{\frac{p_{rnd}}{n\log n}}\right)$ where p_{rnd} is the probability that a node can communicate to any other random node in its range. In [7], the authors present efficient schemes to compute maximum throughput and fair bandwidth allocation in Multi-Radio WMNs. All of the above studies on the capacity of Multi-Channel networks only analyze the transport capacity of ad hoc and mesh networks. They derive generic bounds and do not consider the effect of the channel assignment algorithm and the routing protocol.

For the single channel single radio scenario, Gupta and Kumar [8] showed that in an arbitrary network the per flow capacity scales as $\Theta\left(\frac{W}{\sqrt{n}}\right)$ bit-m/s while in a random network it scales as $\Theta\left(\frac{W}{\sqrt{n\log n}}\right)$ bits/s. In [9], the authors have analyzed the end-to-end call acceptance and derive theoretical bounds in the single channel ad hoc wireless networks. Several other studies regarding the asymptotic capacity of multi-hop wireless networks [10–12] have been conducted. The authors in [3], present a new routing metric WCETT and a corresponding MR-LQSR protocol to