Ad Hoc Networks 51 (2016) 21–35

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Realistic interference-free channel assignment for dynamic wireless mesh networks using beamforming

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ARTICLE INFO

Article history:
Received 2 September 2015
Revised 13 July 2016
Accepted 2 August 2016
Available online 2 August 2016

Keywords:
Beamforming
Channel assignment
Wireless mesh networks

ABSTRACT

To make the most efficient use of scarce bandwidth, channel assignment methods for wireless mesh networks (WMNs) should try to minimize the number of frequency channels used while achieving maximum network throughput. Beamforming is a well-known technique that improves spatial reuse in wireless networks. However, there are no channel assignment methods for WMNs that use beamforming to reduce the number of frequency channels. We develop the first channel assignment method for dynamic WMNs that incorporates beamforming in the conflict graph and matrix. This reduces co-channel interference significantly, thereby reducing the *number of frequency channels required* (NCR) to ensure interference-free communication among the mesh nodes while achieving maximum network throughput. Our novel *Linear Array Beamforming-based Channel Assignment* (LAB-CA) method significantly increases the spectrum utilization efficiency of WMNs at the expense of increased hardware complexity. It outperforms classical *omni-directional antenna pattern-based channel assignment* (OAP-CA) in terms of NCR. In a heterogeneous WMN where mesh nodes have differing numbers of radio interfaces, LAB-CA also outperforms OAP-CA in terms of NCR in both sparse and dense scenarios. A further significant reduction in NCR is achieved when the number of antennas in the linear antenna arrays of mesh nodes is increased.

1. Introduction

It is well known that co-channel interference in wireless networks degrades network throughput. The goal of an effective channel assignment method for multi-radio multi-channel (MRMC) wireless mesh networks (WMNs) is to minimize the number of frequency channels required for interference-free communication among the mesh nodes while achieving maximum network throughput. Beamforming mitigates interference in wireless networks by improving spatial reuse. The full potential of beamforming in WMNs cannot be realized until methods are developed that accurately capture its characteristics in their interference models to minimize the number of frequency channels. To the best of our knowledge, no existing channel assignment method for MRMC WMNs incorporates the necessary beamforming-based interference modeling.

We develop a new and effective channel assignment method that minimizes the *number of frequency channels required* (NCR) to ensure interference-free communication among the mesh nodes for achieving maximum network throughput in a dynamic MRMC WMN. Our novel *Linear Array Beamforming-based Channel Assignment* (LAB-CA) method is the first of its kind to incorporate beamforming in the conflict graph and matrix to minimize co-channel interference and to reduce NCR. As expected, the results show that LAB-CA significantly outperforms classical *omni-directional antenna pattern-based channel assignment* (OAP-CA) in terms of NCR. Preliminary work in this regard appears in [1].

The node-degree of a mesh node is the number of radio interfaces that it has for data communication with its neighbors. In a WMN architecture consisting of *homogeneous mesh nodes*, the node-degree of all mesh nodes is the same. We also study a more realistic WMN architecture consisting of *heterogeneous mesh nodes* (i.e. mesh nodes having different node-degrees). We extend LAB-CA to incorporate heterogeneous mesh nodes and evaluate its performance in homogeneous vs. heterogeneous environments. We find that *LAB-CA for heterogeneous mesh nodes* (LAB-CA_HT) requires more frequency channels as compared to *LAB-CA for homogeneous mesh nodes* (LAB-CA_HG).

We also evaluate the performance of LAB-CA_HT by comparing its performance with *OAP-CA for heterogeneous mesh nodes* (OAP-CA_HT) in both sparse and dense WMNs. We find that LAB-CA_HT outperforms OAP-CA_HT in terms of NCR in both scenarios. It performs even better in dense mesh networks and provides a reduction of at least 58% in NCR.

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http://dx.doi.org/10.1016/j.adhoc.2016.08.001
1570-8705/

In a *multi-radio multi-channel multi-antenna* (MRMCMA) WMN, the number of antennas in the linear antenna array of a multi-radio mesh node is greater than its node-degree. We explore the impact of increasing the number of antennas in the linear antenna arrays of the multi-radio mesh nodes on the number of frequency channels when using LAB-CA_HT in a MRMCMA WMN. We find that a further significant reduction of at least 20% in NCR is achieved when the number of antennas in the linear antenna arrays of mesh nodes exceeds their node-degrees.

Specifically the main contributions of this paper are as follows:

- A new and effective channel assignment method LAB-CA is proposed and evaluated. It incorporates beamforming directly into the conflict graph and matrix for modeling interference in MRMC WMNs as a means to minimize co-channel interference and to reduce the total number of required frequency channels.
- To model a more realistic WMN architecture, the channel assignment framework is extended to incorporate heterogeneous mesh nodes, and the effectiveness of LAB-CA_HT in sparse as well as dense mesh networks is demonstrated.
- A multi-radio multi-channel multi-antenna WMN architecture is proposed, and the effectiveness of using multi-antenna mesh nodes is demonstrated.

The rest of the paper is organized as follows. Section 2 presents the related work in this area. Our model for the network architecture is presented in Section 3. The LAB-CA method is presented in Section 4. The extension of the channel assignment framework that incorporates heterogeneous mesh nodes and consists of LAB-CA_HT is presented in Section 5. Performance evaluation with results is given in Section 6. Conclusions are presented in Section 7.

2. Related work

Channel assignment schemes [2–18] for classical MRMC WMNs typically assume a multi-radio mesh node to be equipped with omni-directional antennas. Using these, a mesh node can communicate with several neighbors simultaneously over different frequency channels. When a pair of mesh nodes are communicating over a certain frequency channel, other mesh nodes within the circular radiation pattern of their omni-directional antennas must not transmit over the same frequency channel to avoid a conflict.

To improve spatial reuse by reducing co-channel interference, DMesh [19] proposes the use of directional antennas for mesh nodes in a MRMC WMN. Directional antennas are used in [20] for directional transmission and reception algorithms for wireless ad-hoc networks. A study of the joint routing and scheduling optimization problem in TDMA-based WMNs [21] assumes that nodes are equipped with directional antennas. In [22], the authors study the problem of building topologies for nomadic WMNs where the degree of any node is less than its number of available directional mesh radios. A topology control method for MRMC WMNs that use directional antennas is proposed in [23]; however such antennas are non-steerable and always point where they were manually directed at the time of installation. Hence they are not useful in a dynamic WMN environment undergoing regular topological changes as new mesh nodes join the network or existing mesh nodes leave it, e.g. due to node failure.

For the successful operation of a self-organizing and dynamic MRMC WMN, beamforming is required instead of directional antennas with stationary radiation patterns. Multiple beams can be formed by using the multiple omni-directional antennas of a multi-radio mesh node in the form of a linear antenna array. Unlike the non-steerable beam of a directional antenna such as a parabolic antenna, the main beam of a linear antenna array can be pointed in any desired direction by controlling the progressive phase difference between the antenna elements of the array. This steerable beam pattern of a linear antenna array can be used in the operation of a dynamic WMN.

Schemes that use beamforming for interference mitigation have been proposed in the literature for TDMA-based single-radio single-channel multi-hop wireless networks [24,25], cellular networks [26], and single-hop wireless ad-hoc networks [27]. In [24], the spatial-reuse-only protocol is proposed, which uses multiple antennas of a wireless node for beamforming to prevent a transmitter's signal from reaching nearby undesired receivers. A multi-antenna beamforming technique is described in [25] to suppress interference and improve spatial reuse. Both [24] and [25] use the protocol model [28] for interference. The authors study a joint base-station association, beamforming, channel assignment and power control problem in heterogeneous cellular networks in [26], where low-power base-stations are overlaid with conventional macro base-stations. The problem of interference suppression is considered in [27] and a joint iterative beamforming and channel allocation strategy is proposed for wireless nodes in an ad-hoc network, where pairs of nodes communicate only with each other. It is assumed that the available frequency band is divided into orthogonal frequency channels of the same bandwidth, and each node is capable of switching between two orthogonal frequencies. Unlike these schemes [24–27], this work deals with the problem of channel assignment in multi-hop multi-radio multi-channel WMNs, where the objective is to assign frequency channels to those links between multi-radio mesh nodes that are required to achieve maximum network throughput such that all of these links can be active simultaneously without any co-channel interference. To the best of our knowledge, LAB-CA is the first channel assignment method of its kind that incorporates beamforming directly in the conflict graph and matrix to significantly reduce the number of frequency channels required for interference-free channel assignment in dynamic MRMC WMNs.

Similar to LAB-CA_HG, the channel assignment schemes in [3,4,8,10,13,17] assume that the node-degrees of all mesh nodes in the network are the same. The topology-controlled interference-aware channel-assignment algorithm (TICA) [3] uses four radio interfaces at each mesh node. The breadth-first-search channel assignment (BFS-CA) scheme [7] requires that a certain number of mesh routers with a certain number of radio interfaces are placed at certain hops from the gateway, whereas LAB-CA_HT does not require any careful mesh router placement strategy. While evaluating the performance of the max-flow-based channel assignment and routing (MCAR) scheme [9], the authors consider two classes of topologies with 25 and 50 mesh nodes. In the 25-node network, 60% of the mesh routers are assigned 2 radios while the remainder are assigned 3 radios. In the 50-node network, 20% of nodes have 2 radios, 40% have 3 radios and 40% have 4 radios. For each class, 20 different topologies are generated having different placements of nodes. LAB-CA_HT works with any random number of radio interfaces at the mesh nodes; in our experiments we choose this number from a uniform random distribution.

Different channel assignment schemes have used different WMN sizes in their performance evaluations. The centralized hyacinth (C-HYA) scheme [4] used a 100-node mesh network. The distributed hyacinth (D-HYA) scheme [6] used a 60-node mesh network. A topology consisting of 30 mesh nodes was used for the performance evaluation of BFS-CA. The simulation experiments on the traffic and interference aware channel assignment scheme (MesTiC) [8] used a 25-node mesh network. TICA was evaluated using a 36-node mesh network. Two classes of topologies with 25 and 50 mesh nodes respectively were used to evaluate MCAR. In [17], two different deployments consisting of 36 and 60 mesh nodes were used. The channel assignment method is simulated using two sets of networks in [10]; the dense network has 50 mesh