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Optimal Resource Assignment in Wireless Mesh Networks

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***Abstract*—Wireless Mesh Networks (WMNs) are new emerging multi-hop wireless networks that offer low-cost high-bandwidth community wireless services. Much work has been done so far in order to enhance the performance of these networks. In this paper, by using a simplified version of the optimization framework provided by Antonio Capone et al., we study the impact of using some advanced wireless communication techniques on the performance improvement of WMNs. These techniques are using multiple radios/multiple channels (MR-MC), dynamic power control, and rate adaptation. In this way, we use network optimization algorithms based on joint routing, link scheduling and static channel assignment. Simulation results show that using power control, rate adaption and MR-MC strategy significantly improves network efficiency in terms of throughput, load balancing and delay.**

***Index Terms*— Wireless Mesh Network, Multi-radio Multi-channel, Resource Assignment.**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are cost-effective solutions for providing ubiquitous high-speed services. The infrastructure of a WMN consists of a number of wireless mesh routers interconnected to provide Internet access to fixed and mobile network users. This infrastructure can be connected to Internet by using special routers called gateways [1].

In WMN, the backbone is devised to provide resource assignment to traffic flows between user stations and network gateways. In this way, cross-layer optimal resource assignment mechanisms appear to be a key element in providing bandwidth guarantees to traffic flows. In providing QoS for wireless mesh networks, routing is an important component. On the other hand, choosing the proper path for data transmission is dependent on the capacity of network links which are specified by link scheduling and channel assignment. It can be concluded from above statements that the optimal performance can be achieved by joint optimization of routing, link scheduling, channel assignment, power control and rate control. In fact, the cross-layer design of resource assignment strategy is the most appropriate tool able to provide QoS for traffic flows and to achieve high network efficiency [2]. However, it has risks due to the loss of layer abstraction and incompatibility with existing protocols. Thus, for using cross-layer design, certain guidelines must be followed. In [3], authors state the motivations for cross-layer design in WMNs. Moreover, they provide guidelines for carrying out cross-layer design by investigating different schemes for cross-layer optimization.

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Optimization approaches to different types of scheduling problem, routing problem, channel assignment problem or joint of them have been considered within the general framework of multi-hop wireless networks recently.

In [4], a solution for joint routing and scheduling in WMNs with the aim of improving the network throughput is proposed. In [5], authors propose a hierarchy capacity optimization model with the aim of optimizing link scheduling. Also a linear programming model for joint channel allocation and routing is proposed. Reference [6] introduces three static channel assignment algorithms and discusses about the benefits and shortcomings of each. In [7], authors propose an interference-aware channel allocation algorithm for MR-MC WMNs to minimize interference within and between the mesh network and co-located wireless networks. In [8], we introduced a load-aware cost function for multicast routing which distributes the traffic among the nodes fairly.

In [9], authors propose an optimization framework for WMNs that includes joint routing, scheduling and channel assignment. In this paper, by using the optimization framework provided in [9], we study the impact of using some advanced wireless communication techniques on the performance of WMNs. These techniques are using multiple radios/multiple channels, dynamic power control and rate adaptation based on SINR. In [9], authors only consider the number of time slots as a metric to evaluate the performance of the algorithms. In this paper, we consider not only the number of time slots but also practical QoS metrics such as throughput, delay and load balancing criterions to show the goodness of the strategies.

The rest of the paper is organized as follows. In Section II, we present the system model and in sections III and IV, we develop the formulations for fixed power-fixed rate (FP-FR), power control-fixed rate (PC-FR) and power and rate control (PRC) cases for single radio/single channel (SC-SR) and multi-radio/muti-channel (MC-MR) scenarios, respectively. In Section V, we show some numerical results on random topologies. Finally, we provide some concluding remarks at the end of the paper.

II. SYSTEM MODEL

Consider a TDMA-based wireless mesh network with N static nodes and L links. We model this network as a directed graph $G(V,E)$, where $V = \{1, 2, . . . , N\}$ represents the set of routers and $E = \{1, 2, . . . , L\}$ represents the set of links. Each link corresponds to a pair of transmitting and receiving routers. Here, we consider some traffic flows, where *Demands* is the set of node pairs (o,d) and $demand(o,d)$ is the number of packets should be sent from node o to node d in a time frame. Note that in our model, time frames are assumed to be consisting of fixed length time slots. Therefore, in the rest, traffic demands are translated into the number of fixed length packets per time frame, while, transmission rates are translated into the number of packets per time slot.

In this paper, we use Physical Model as our interference model. In Physical Model, when a single rate is considered, SINR constraint is $SINR_j \geq \gamma$ for all $j \in V$ where $SINRj$ is the SINR level at receiver j and γ is the minimum required SINR. When multiple rates are considered, SINR constraint is $SINR_j \geq \gamma_w$ for all $j \in V$ where γ_w is the minimum required SINR when rate w is adopted. It is clear that $SINR_j$ is function of p_i, G_{ij} and η_j, where p_i is the power transmitted by transmitting node i, G_{ij} is the gain of the radio channel between i and j, and η_j is the thermal noise at receiver j.

In this paper, similar to [9], we define a feasible configuration as the set of links that can be active simultaneously in a time slot without violating the SINR constraint. In this way, *Sets* is defined as the set of all feasible configurations, $set_{i,j}$ is defined as the set of feasible configurations that include link (i,j), and integer variable $active_q$ is defined as the number of slots in which configuration $q \in Sets$ is active.

In our optimization framework, we must assign the time slots to links such that bandwidth constraints are satisfied. In other words, we must obtain the minimum number of required time slots to deliver the traffic demands to the destinations. Note that, in each time slot, only one feasible configuration can be active.

To study the impact of different wireless communication techniques, we consider two different scenarios. In first scenario, we assume a single radio/single channel (SR-SC) wireless mesh network. In second scenario, we consider the new emerging class of wireless mesh networks with multi-radio/multi-channel (MR-MC) nodes. Utilizing multi-radio devices in a multi-channel network considerably increases the efficiency of WMNs as we can have parallel non-interfering transmissions on non-overlapping channels. However, due to the limited number of radios and the limited number of non-overlapping channels, some links interfere with each other and cannot be active at the same time. Thus, a proper channel assignment strategy is essentially required to improve the performance of the network. Channel assignment methods, can be divided into two types: dynamic channel assignment in which the channel assignment to radios can be changed slot-by-slot and static channel assignment in which radios are statically tuned to a channel and the assignment cannot be changed for the entire frame duration. In this paper, we use static channel assignment strategy, because switching delay from one channel to another is considerable and therefore, dynamic channel assignment practically hasn't much usage.

In next section, first we consider SR-SC scenario, and then in section IV, starting from the solutions obtained for SR-SC scenario, we obtain a MR-MC solution by assigning a channel to every activated configuration. In each scenario, we consider three different cases: Fixed Power-Fixed Rate (FP-FR), Power Control-Fixed Rate (PC-FR), and Power and Rate Control (PRC).

III. SINGLE RADIO/SINGLE CHANNEL SCENARIO

A. *Fixed Power - Fixed Rate (FP-FR)*

First, consider a WMN in which each node is equipped with a single radio working on a common channel. Also, assume that the transmitting power of each node is equal to a fixed value *p*. In this scenario, feasible configurations are those satisfy two kinds of constraints: nodes can't transmit and receive at the same time (half-duplex constraint) and SINR constraint is given by

$$pG_{ij} \geq \gamma\Big(\eta + \sum_{\substack{(h,j)\epsilon q \\ h\neq i}} pG_{hj}\Big) \qquad \forall q \in Sets,\ \forall (i,j) \in q. \tag{1}$$

Here, the optimization problem can be modeled as [9]:

$$min \sum_{q \in Sets} active_q \ , \tag{2}$$

Subject to

$$\sum_{(i,j)\epsilon L} flow_{ij}^{od} - \sum_{(j,i)\epsilon L} flow_{ji}^{od} = \begin{cases} demand(o,d) & i = o \\ -demand(o,d) & i = d \\ 0 & otherwise \end{cases} , \tag{3}$$

$$\forall i \in N, \forall (o,d) \in Demands$$

and

$$\sum_{q\epsilon set_{i,j}} rate_q \times active_q \geq \sum_{(o,d)\epsilon Demands} flow_{ij}^{od} \qquad \forall (i,j) \in L. \tag{4}$$

where $rate_q$ is the maximum number of packets that can be transmitted on links in a time slot for configuration *q*. For fixed rate problem, $rate_q$ is always equal to 1. $flow_{ij}^{od}$ is the number of packets routed from node *o* to node *d*, passing on link *(i,j)* in a time frame. In this problem, objective function (2) minimizes the number of used time slots subject to the constraints (3) and (4).

B. *Power Control - Fixed Rate (PC-FR)*

For the case of PC-FR, we introduce two new sets of variables: non-negative continuous variable $p_{i,q}$ which represents the transmitted power of node *i* in configuration *q*, and binary variable u_q for each configuration *q* which is equal to one if configuration *q* can satisfy power control constraints and is zero otherwise.

First, we determine all configurations that satisfy half-duplex constraint, and then we choose between them configurations that also satisfy power constraint. We can model this process as

$$max \sum_{q \in Sets} u_q \ , \tag{5}$$

Subject to

$$p_{i,q}G_{ij} \geq \gamma\Big(\eta + \sum_{\substack{(h,j)\epsilon q \\ h\neq i}} p_{h,q}G_{hj}u_q\Big) \qquad \forall q \in Sets,\ \forall (i,j) \in q, \tag{6}$$

and

$$p_{i,q} \leq P_{max} \qquad \forall q \in Sets,\ \forall i \in N. \tag{7}$$

All feasible configurations can be found by solving the objective function (5) subject to constraints (6) and (7), where *Pmax* is the maximum power that can be transmitted by nodes. The problem formulation for minimizing the number of time slots in PC-FR case is the same as FP-FR, except that in Equations (2) and (4), $active_q$ must be replaced by $active_q \times u_q$.

C. Power and Rate Control (PRC)

In this case, an available rate w from set W must be assigned to each configuration, where γ_{wq} is defined as the SINR threshold corresponding to rate w in configuration q. The problem formulation for finding feasible configurations and minimizing the number of time slots is the same as PC-FR case, except that in all equations, γ must be replaced by γ_{wq}.

IV. MULTI RADIO/MULTI CHANNEL SCENARIO

In this section, using the solutions obtained for SR-SC scenario, we are going to obtain a MR-MC solution by assigning a non-overlapping channel to every activated configuration. In MR-MC scenario, the number of active configurations at each time slot should be smaller than the number of non-overlapping channels. In addition, the maximum number of active channels per node is equal to the number of its radios. First, we define H as the set of time slots, C as the set of active configurations (obtained from SR-SC scenario), I as the number of radios per node, and O as the set of non-overlapping channels. Also, we define some binary variables: A_{ci} which is equal to 1 if node i appears in configuration c and is equal to 0 otherwise, t_h which is equal to 1 if slot h is used in the resulting frame and is 0 otherwise, y_{ch}^f which is equal to 1 if configuration c is assigned to time slot h with channel f and is 0 otherwise and r_{if} which is equal to 1 if node i uses channel f and is 0 otherwise.

The problem of cross-layer design in MR-MC case can be formulated as [9]:

$$min \sum_{h \in H} t_h, \tag{8}$$

Subject to

$$\sum_{h \in H} \sum_{f \in O} y_{ch}^f = 1 \qquad \forall c \in C, \tag{9}$$

$$\sum_{c \in C} y_{ch}^f \le 1 \qquad \forall h \in H, \ \forall f \in O, \tag{10}$$

$$\sum_{c \in C} \sum_{f \in O} y_{ch}^f \le |O| \qquad \forall h \in H, \tag{11}$$

$$r_{if} \ge \sum_{h \in H} y_{ch}^f A_{ci} \qquad \forall i \in N, \forall c \in C, \forall f \in O, \tag{12}$$

$$\sum_{f \in O} r_{if} \le I \qquad \forall i \in N, \tag{13}$$

$$y_{ch}^f \le t_h \qquad \forall c \in C, \ \forall h \in H, \ \forall f \in O. \tag{14}$$

Constraint (9) guarantees that each configuration is assigned to a time slot. Constraint (10) states that in each multi-channel time slot, we can assign at most one configuration per channel. Constraint (11) guarantees that the number of channels assigned in each time slot doesn't exceed the number of available non-overlapping channels. Constraints (12) and (13) state the constraints in assigning non-overlapping channels to radios of a node. Finally, constraint (14) regulates multi-channel time slot activation.

V. NUMERICAL RESULTS

For solving the developed formulations, we used modeler AMPL and solver CPLEX 12.2. Computations have been run on a PC with Intel Core i5 at 2.67 GHz and 4 GB RAM under Microsoft Windows. In all simulations, we consider the following assumptions: SINR thresholds are 2, 2.8, 7.1 and 15.9 for transmission rates 1, 2, 4 and 8 packets per time slot, respectively. Channel gain G_{ij} between node pairs i and j is set to d_{ij}^{-3}, where d_{ij} is the distance between the nodes i and j, η is 10^{-11} Watts, number of radios per node is equal to 3 and there is 6 non-overlapping channels can be assigned to radios.

For simulation, we consider a set of randomly generated topologies with 10, 15 and 20 nodes. The topologies have been generated by randomly locating the nodes over a 1000m square area. Traffic demands are defined by randomly selecting the node pairs and the traffic volume is randomly selected between 1 to 15 packets per time frame. In each case, fifteen different instances with the same number of nodes have been generated and the results are averaged.

In our performance analysis, the evaluation metrics are:

1- *Throughput (capacity)*: Assuming a limited number of time slots per time frame, throughput is defined as the maximum number of packets that can be routed on the network per time frame. We can calculate throughput by repeated generation of many small traffic demands (for example 1 packet per time frame) between uniformly random selected nodes. For each demand, if there is enough bandwidth on the active topology, we route it to destination, otherwise we stop the process. The total number of successfully routed packets indicates the throughput. In simulations, for calculating throughput, we assume at most 300 time slots per frame.

2- *Number of required time slots*: is defined as the minimum number of time slots are required to deliver the traffic demands to their destinations. It is clear that for predefined traffic demands, average delay is directly proportional to the number of required time slots.

3- *Variance of nodes utilization*: is the variance of the total traffic loads on nodes. It indicates the degree of load-balancing over nodes in the network. Smaller variance of nodes utilization indicates more balanced network.

4- *Variance of links utilization*: is the variance of the total traffic loads on links. It indicates the degree of load-balancing on links in the network. Smaller variance of links utilization indicates more balanced network.

The simulation results are shown in Tables I-V. In Tables I and II, both scenarios (SR-SC and MR-MC) are considered for different network sizes, but in Tables III to V, only SR-SC scenario is considered.

As you can see from results, using MR-MC instead of SR-SC improves the efficiency by decreasing the required time slots and average delay. Also, numerical results show that using power control and rate control clearly improves the performance metrics of the network. It is also interesting to note that the performance metrics improve when the network size increases. This is because the optimization algorithm can choose more alternative paths exploring a larger solution space.

TABLE I. NUMBER OF REQUIRED TIME SLOTS IN SR-SC SCENARIO

	FP-FR	PC-FR	PRC
10 nodes	65.83	53.58	11.11
15 nodes	59.17	49.92	9.08
20 nodes	57.25	41.58	7.84

TABLE II. NUMBER OF REQUIRED TIME SLOTS IN MR-MC SCENARIO

	FP-FR	PC-FR	PRC
10 nodes	19.5	17	4.33
15 nodes	17.92	15.75	3.17
20 nodes	16.9	13.67	2.75

TABLE III. VARIANCE OF NODES UTILIZATION IN SR-SC SCENARIO

	FP-FR	PC-FR	PRC
10 nodes	0.00627	0.00471	0.00201
15 nodes	0.00532	0.00349	0.00136
20 nodes	0.00255	0.00185	0.00079

TABLE IV. VARIANCE OF LINKS UTILIZATION IN SR-SC SCENARIO

	FP-FR	PC-FR	PRC
10 nodes	0.00025	0.00018	6.31E-05
15 nodes	0.00011	5.36E-05	8.82E-06
20 nodes	3.35E-05	1.75E-05	1.21E-06

TABLE V. THROUGHPUT IN SR-SC SCENARIO

	FP-FR	PC-FR	PRC
10 nodes	372.5	452.58	1900.83
15 nodes	398.91	489.27	2096.93
20 nodes	419.44	503.8	2115.96

VI. CONCLUSIONS

In this paper, by using a simplified version of the optimization framework developed by Antonio Capone et al. in [9], we studied the impact of using some sophisticated wireless communication techniques on the performance improvement of WMNs. These techniques are using multiple radios per node and using multiple non-overlapping channels, using power control and applying rate control. Numerical results showed that using these techniques significantly increases the network throughput, decreases average delay and improves the load balancing in the network.

It is clear that using more radios per node allows more simultaneous transmissions on different non-overlapping channels in each time slot and this improves the network efficiency. Simulation results showed that using MR-MC instead of SR-SC can give considerable reduction in the required time slots and average delay.

With power control, transmission power can be set in order to just reach the SINR threshold at the receiver; therefore, the potential interference between nodes can be reduced considerably. As a result, the number of required time slots will be decreased that leads to greater throughput and less delay. On the other hand, in this case, usually longer paths with shorter hops will be used in comparison to the fixed power case. This offers better load balancing across links and nodes.

In the context of transmission rate control, by increasing the transmission rate, the transmission time will be decreased. This means that the higher transmission rates take less time slots on scheduling frame. In contrast, by increasing the transmission rate, the receiver sensitivity threshold will also be increased. Assuming fixed transmission power, this decreases the transmission range. In this case, by using both power and rate control; it is clear that we can optimize the transmission and interference ranges of the nodes. In this way, simulation results showed that using both power control and rate control clearly improves the performance metrics of the network.

In practice, the technique developed in this paper can be used widely in the analysis and design of modern wireless mesh networks. Also in research efforts, the developed model can be used as a baseline for comparing the proposed heuristic algorithms with the optimal case.

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