Reducing Antenna Beam Switchings in STDMA Based Wireless Mesh Networks

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Abstract: In this paper, an algorithm is proposed that minimize the overall number of required beam switches in a wireless mesh network with directional antennas without deteriorating the spatial reuse of timeslots. Simulation results suggest that the proposed algorithm can reduce the number of beam switches by almost 90% without affecting the frame length of the network.

1. Introduction

Wireless Mesh Networks (WMNs) have recently emerged aiming to provide broadband wireless Internet connectivity and/or backhaul support for cellular networks without the need of a costly wired network infrastructure [1]. The deployment of directional antennas in WMNs has been analyzed [2] over the last few years and it is already proved that they ameliorate the spatial reuse of resources in the network. Regarding the medium access control scheme, we focus on spatial time division multiple access (STDMA). Since nodes are spatially distributed, timeslots can be potentially reused by nodes that are sufficiently far apart, as have been defined by Kleinrock [3]. The application of directional antennas in conjunction with collision free scheduling algorithms has shown to considerably reduce the overall frame length in STDMA, compared to the scenario where omnidirectional antennas are employed. Switched beam antennas are formed by several available fixed beam radiation patterns; an antenna uses different patterns depending on the direction towards a communication need to be established. The change of radiation pattern in an antenna is called in the literature as a *switch*. Each time a switch is performed, the beam switched antenna consumes energy (≈ 40μW) and requires an amount of fixed time (between 5μs to 0.25ms) to stabilize the new radiation pattern [4] [5]. The key objective of this paper is to provide an efficient algorithm for minimizing the number of beam switchings in the WMN without penalizing the timeslot allocation.

2. System Model

We consider a WMN, which can be modelled as a graph $G(V,E)$, where V expresses the set of nodes and E denotes the set of wireless links. We further assume that all nodes in the mesh network operate at the same frequency band and the packet length is normalized and occupies a single timeslot.

2.1 Antenna Model

Each node in the WMN is equipped with a switched beam by using phase array antennas forming a radiation pattern with K identical and selectable beams. The radiation pattern of a beam is approximated by a main lobe of constant gain g_m and beamwidth θ_m and a side lobe of constant gain g_s and beamwidth $(2\pi - \theta m)$. We assume that the direction of each beam is fixed and the boresights of the first sector are always directed towards the 0^o and θ_m on a polar plane. When a link need to be established between nodes i and j, then node i calculates the relative angle, between the 0^o in the polar plane and link (i, j) to determine the employed antenna beam.

To model directional antennas it is necessary to find an expression that relates the gains and beamwidth with the total amount of energy transmitted by an omnidirectional antenna with unit gain. The model used hereafter, assumes a 2 dimensional radiation pattern to calculate the parameters of a directional antenna. Equation 1 relates the parameters of the directional antenna.

$$\mathrm{g_m}\frac{1}{2\pi}\theta_\mathrm{m} + \mathrm{g_s}\frac{1}{2\pi}(2\pi - \theta_\mathrm{m}) = 1 \qquad (1)$$

Equation 1 expresses how the total amount of transmitted power is spread between the main and side lobes. This same equation is also valid when $Nb > 1$ beams are activated simultaneously. In that case, it is considered an antenna that has a main lobe with beamwidth $Nb \cdot \theta_m$ and a side lobe with beamwidth $(2\pi - Nb \cdot \theta_m)$.

2.2 Interference model

For a single transmission bit-rate, each link $(i, j) \in E$ needs to satisfy a signal to interference noise ratio (*SINR*) threshold (γ) for successful packet decoding. The *SINR* inequality that needs to be satisfied to ensure the feasibility of link (i,j) can be written as follows,

$$\frac{g_{ij}A_{ij}^{ab}p_{ij}}{\sum_{(m,n)\in E\backslash\{(i,j)\}} g_{mj}A_{mj}^{cd}p_{mn} + W} \geq \gamma \qquad (2)$$

in the above expression p_{ij} denotes the transmission power for link (i, j), g_{ij} is the link gain for link (i, j), A_{ij}^{ab} is the antenna gain of the transmission node i when using beam pattern a multiplied with the antenna gain of the receiver node j with pattern b and W expresses the power of background and thermal noise. Note that each antenna can have a number of different patterns depending on which beams are active at the same time. Additionally, the following path loss model for link *(i,j)* is used, $PL(d(i,j)) = PL(d_0) + 10\eta \log_{10}(d(i,j)/d_0)$ where $d(i, j)$ is the distance of link *(i, j)*, $PL(d_0)$ is the close in distance loss for distance d_0, and η is the path loss exponent.

2.3 Set up of the WMN

The WMN topology is deployed in a square area AxA Km^2 containing N wireless nodes that are randomly and uniformly distributed over the squared area. A special node in the topology acts as the gateway node for providing Internet connectivity; throughout the numerical investigations a single gateway node is considered. Based on all feasible links that can be constructed when no co-channel interference is considered, a shortest path spanning tree is constructed rooted at the gateway node spanning all other nodes in the network. The spanning tree is based on the minimum power routing (MPR) scheme, as described in [6]. The MPR scheme is based on Dijkstra's algorithm and uses the required transmitted power to combat the path loss as the cost of the link. The power transmitted by a node in the network is determined by the minimum power required to establish a communication with a receiver node in absence of interference as long as it does not exceed the maximum power transmitted (P_{max}). The power required by a node i to establish a link with node j is calculated considering omni-directional antennas with unit gain. Directional antennas are not employed to calculate the power requirements for establishing a link to ensure that if the antenna pattern of a node has been modified, the antenna will have enough power to establish the link.

Since a shortest path spanning tree is created, the links that need to be scheduled are ($N - 1$) in all numerical investigations. Furthermore, scheduling is taking place under the assumption that a node cannot transmit and receive at the same timeslot. In this paper, links are scheduled using the Greedy Physical algorithm, which is explained in detail in [7], but the proposed technique for reducing the number of beam switches is actually independent of the scheduling algorithm employed. Finally, we consider the often-used scenario where each link requires to be scheduled in only one timeslot.

3. A Beam Joining Algorithm

Initially each link in the network has assigned one radiation pattern for the receiving antenna and one for the transmitting antenna and each pattern is initially formed by only one beam. We further assume that the timeslot allocation is not feasible when all nodes operate in an omnidirectional mode (that case would negate the need to decrease the number of beam switches).

Observe that joining different beams implies that when a node i wants to transmit to a neighbour node j, its power will be spread along several beams of the antenna instead of just along one beam. As a result, there will be an increase of the interference in the regions where there was not any active beam before the joining. Increasing levels of interference across the network caused by joining different beams of an antenna may create an infeasibility on the timeslot allocation. Therefore, to reduce the number of beam switching in the network suitable beam joining should be performed at each node to enhance the switch reduction.

Patterns are suitable to be merged whether they are different or even being equal the links that use these patterns are different. The first situation is quite obvious since the aim of the algorithm is to join different patterns in order to decrease the number of switches. The second case could be more confusing as joining equal patterns does not lead to a reduction of the switches. However, patterns are not considered initially merged in order to give more flexibility to the joining procedure.

The basis upon which the algorithm is designed is to find the beam that is causing less interference to its neighbours in the network and try to join this beam (considering that this beam might be already joined with other beams) with the next beam from the same antenna (which might be also joined with others) that causes less interference. In order to do that, a metric that measures the interference that a transmitting link causes need to be used. In our algorithm, we employed the interference number (IN) defined in [7], since it serves as a good approximation to find the pair of patterns that are causing less interference to the network. The interference number of a link $(i,j) \in E$ is the number of links $(m, n) \in E \setminus (i, j)$ that cannot establish a communication at the same time such the links *(m, n)* and *(i, j)* do not share an endpoint and is infeasible. In this algorithm, we calculate the IN with the initial radiation patterns (where all patterns are formed by single beams).

Two approaches can be applied to decide whether a merged is accepted or not. Initially, a fixed link schedule was assumed and joining antenna beams was accepted only if the link schedule remained feasible. Note that only the set of links scheduled in those timeslots that contain a link whose pattern has been modified, need to be checked to ensure the feasibility of the schedule. The pseudo-code of the proposed scheme is shown in algorithm 1. However, joining beams causes a change of the antenna patterns, and so in its gains, which implies a redistribution of the interference that nodes cause to each other. In consequence, re-allocating the links each time a beam joint is performed, might take profit of this redistribution allowing more simultaneous beams to be activated at the same time. Hence, each time a pattern is modified, instead of checking the feasibility of the corresponding links in the network, we may re-schedule all links in order to redistribute more efficiently the interference. Thereby, a beam joint is successful if the new schedule has the same or less number of timeslots as the initial schedule since it is not the purpose of this paper the reduction of switches at the expense of deteriorating the timeslot allocation. At the bottom part of algorithm 1 is shown how to modify the algorithm to allow re-scheduling.

Algorithm 1: Beam Joining algorithm

```
Input  : G = (V, E), E(v) denotes the set of all
       : edges in E at a vertex v.
       : r, uniformly distributed [0, 1] random
       : variable.
       : p ← 0.5
       : L, List containing all links sorted in
       : increasing order by its IN.
       : S, A feasible schedule with length TS.
       : Gains, gains of all patterns.
Output : Patterns, List of all patterns and their
       : respective associated patterns that are
       : activated at the same time.
       : S, A feasible schedule with length TS.

1:  for i ← 1 to |L| do
2:    [u, v] ← L(i), where (u,v) are the nodes of link i
3:    if r > p then
4:      A[1] ← u; A[2] ← v
5:    else
6:      A[1] ← v; A[2] ← u
7:    endif
8:    for k ← 1 to 2 do
9:      Ls ← E(A[k]) \ L(i)
10:     Ls ← OrderbyIN(Ls)
11:     jointSuccess ← 0
12:     j ← 0
13:     while j < |Ls| and jointSuccess = 0 do
14:       j ← j + 1
15:       if Candidates(L[i], Ls[j]) then
16:         Temp_Patterns ← Join(L[i], Ls[j])
17:         Temp_Gains ← Update_gains(L[i], Ls[j])
18:         if Feasible(S) then
19:           jointSuccess ← 1
20:           Patterns ← Temp_Patterns
21:           Gains ← Temp_Gains
22:         endif
23:       endif
24:     endw
25:   endfor
26: endfor
27: % Modification to apply re-scheduling.
28: % Add after line 17
    TS_new, S_new ← Calculate_Schedule(), with the
    updated Patterns
29: % Substitute if condition at line 18 and add after.
30: if TS_new ≤ TS then
31:   S ← S_new
```

Undoubtedly, re-scheduling permits a higher reduction of switches, however this approach is less computationally efficient since requires the re-allocation of the links each time beams are jointed. The re-allocation might be complete or partial depending on the scheduling algorithm employed. For instance, if we use a packing algorithm, as the Greedy Physical employed here, we don't need to re-scheduled the set of links, from the first link until the previous link of the first link that its radiation patterns has been modified in the Packing List of the algorithm (which contains all links sorted by the order in which they have been packed), since they will remain in the same timeslots as the original schedule calculated.

4. Numerical Investigations

The results presented hereafter are the averaged values over 200 randomly generated WMN topologies within an area of 850m x 850 m; we use d_0 = 50m, η = 3.5, SNR = 15 db, γ = 8 dB, P_{max} = 20 W, W = -132 dBW and fc = 3.8 GHz.

Figure 2 (right) shows how the performance is improved by utilizing directional antennas. As expected, the spatial reuse decreases as the directionality of the antennas diminishes. This expected behaviour occurs since directional antennas focus most of their transmitted power in an area controlled by the beamwidth of the main lobe; as the beamwidth increases larger areas are interfered and, as a consequence, this affects the spatial reuse of timeslots. Finally, observe that the improvement is becoming more significant as the number of nodes of the network increases.

A similar behaviour for the spatial reuse with directional antennas can be observed for the reduction of the number of beam switchings. The reduction of switches increases as the directionality of the antenna beam increases, as can be noted from figure 2. Observe from this figure that as the number of nodes increases the percentage of switches reduced after applying algorithm 1 might decrease. However, this does not mean that the absolute value of beam switches saved has diminished, since as the number of nodes increases the initial number of switches augments and therefore more switches can be saved.

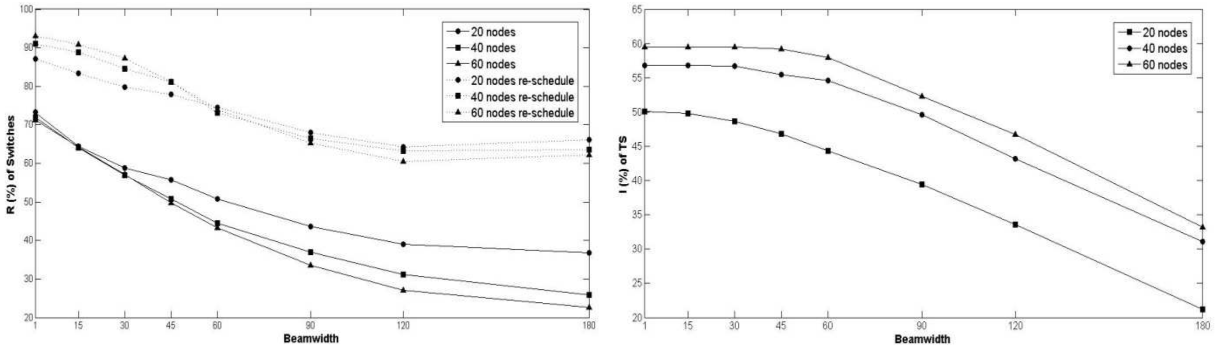

Figure 2:(left) Number of switches reduced (in percentage) compared to the initial switches with directional antennas depending on their beamwidth.(right) Reduction of timeslots employing directional antennas compared to employing omnidirectional antennas.

In figure 2 (left) we also evaluate the reduction in the number of beam switches in the case where a fixed scheduling is considered or when link re-scheduling is allowed. When re-scheduling of the links is permitted, the scheduling algorithm is able to gain from the redistribution of the interference, entailing in an increased reduction of the number of beam switches. Hence, as it was expected, rescheduling the links in the WMN can considerably decrease the number of switches, although the computational complexity increases compared to the other case.

5. Conclusions

In this paper it is shown how by jointly considering beam switching and link scheduling the number of beam switches can be dramatically decreased. A wide set of numerical investigations reveal that the number of beam switches can be reduced by almost 90% without affecting the frame length of the network. Eventually, note that to increase the speed of the algorithm presented here, instead of merging beams one by one, several joints can be performed at the same time. Therefore, the number of times that a schedule needs to be check if it is feasible or the number of times that links have to be re-schedule can be reduced.

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