Increasing end-to-end fairness over IEEE 802.11e-based wireless mesh networks

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SUMMARY

In this paper, we discuss the issue of fairness in the IEEE802.11e over wireless mesh networks. Fairness is an important factor that we have to achieve before talking about QoS. Inspired by social networks approximations, and to achieve fairness and provide QoS by regulating heterogeneous traffic, we extended the original IEEE802.11e protocol by introducing a new algorithm based on the ‘token bucket’ concept. We also treat the problem of exposed/hidden nodes. Simulation results show that the proposed approach offers better performance than the IEEE802.11e one. Copyright © 2011 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The future of wireless networks is involved in the objective of providing users with simpler ways to get connected while providing better service quality. Wireless mesh networks (WMNs) have emerged recently as a promising technology for future broadband wireless access [1] and are gaining significant attention as possible ways to guarantee wireless services. Applying this technology over a shared wireless medium with limited spectrum include many new challenges such as fading mitigation, QoS routing, efficient medium access control (MAC), call admission control, resource management, etc.

WMN deployment can be based on components that are already available in the form of an ad hoc network routing and IEEE802.11 MAC protocols. However, the present IEEE802.11 performs poorly in network capacity and sometimes cannot achieve the theoretical desired capacity bound nor provide service differentiation among traffic of different classes. Both are caused by collisions and retransmission in the shared wireless medium. Thus, to efficiently deploy the IEEE802.11 in a WMN, considerable research efforts are still needed, because the existing protocols applied to WMNs do not support scalability. In addition to this, the throughput drops significantly increase as the number of nodes or hops in a WMN increases [1].

The IEEE802.11 employs a carrier sense multiple access mechanism with collision avoidance, called Distributed Coordination Function, as a basic access method. Even with the acquisition mechanism, called request to send/clear to send (RTS/CTS), Distributed Coordination Function cannot completely eliminate the adverse effects collision and retransmission because of exposed/hidden nodes [6, 10]. The exposed/hidden terminal problem has an important impact on the throughput

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degradation, mainly in multihop ad hoc networks [5, 11]. Resolving the exposed/hidden nodes problem is the key to provide high performance in the mesh networks.

WMNs based on the IEEE802.11e are supposed to support wireless multimedia communications. Because of heterogeneous traffic types, different QoSs to ensure are required such as throughput guarantee for delay and bandwidth sensitive applications. However, because of 802.11e unfairness and collisions that increase transmission delay or cause packet loss, the current shared wireless medium cannot guarantee QoS provisioning. Therefore, to tackle these problems, 802.11e should be enhanced to ensure efficient and fair communications in WMNs [4, 8].

The IEEE802.11e is based on flow priorities to ensure QoS. The issue of fairness is not resolved. The IEEE802.11e priorities act at the MAC layer in its service differentiation but not in the network access [7]. This latter is supposed to be sensitive to the environment and have knowledge of neighbors. It can be noticed when a mesh router with lower priority traffic is located between two nodes with higher priority traffic. The node would suffer bandwidth loss caused by the Transmit Opportunity (TxOP) of the IEEE802.11e and flow priority mechanisms preventing it from communicating immediately.

In this article, we propose a new approach to dynamically configure mesh nodes. We extended the IEEE802.11e by introducing a new mechanism to guarantee fairness and QoS. Furthermore, the proposed algorithm can manage the exposed/hidden nodes problems. This approach is based on the ‘token bucket’ concept. Through Network Simulator NS-2 simulations, we measure the effectiveness of the proposed approach and demonstrate that our solution offers better performance than the standard IEEE802.11 and improves fairness across different flows of QoS ensuring high network throughput.

The rest of the paper is organized as follows: after reviewing some background information related to the fairness problem in wireless mesh networks in Section 2, the core of the proposed algorithm is discussed in Section 3. Section 4 presents performance simulation results of the new scheme compared with the normalized IEEE802.11e one. Conclusions and discussions are given in Section 5.

2. RELATED WORKS

In wireless mesh networks, a fairness problem is observed when:

- The traffic is generated for one-hop communication to a directed neighbor.
- At the end-to-end traffic where flows sent by a given source travel across many nodes to the receiver.

Many research studies have started to revisit the protocol design of IEEE802.11 especially ad hoc networks and wireless sensor networks, from the perspective of WMNs.

Several solutions have been proposed to improve MAC performance. Most of these solutions are based on service prioritization to support QoS requirements. The access to the channel is controlled by Backoff procedures and contention window size. Then, service differentiation is supposed to be achieved by adjusting the Backoff timer [13].

In [2], Bejerano et al. proposed an algorithm that ensures max–min fair bandwidth allocation of both wireless and backhaul links. They showed the correlation between fairness and load balancing to obtain an optimal max–min fair bandwidth allocation.

In [3], Gambiroza et al. studied per-TAP (transient access point) fairness and end-to-end performance in multihop WMNs. Their solution is based on a parking lot-like scenario, where nodes attempt to communicate with a single gateway. However, their algorithm does not support QoS.

To provide QoS over the IEEE802.11e different traffic flows are identified by different access categories (AC) and are assigned to different contention windows. However, the IEEE802.11e provides only statistical priority and the Backoff timer of each AC will count down whenever the channel is idle for the same duration. However, the performance of high-priority traffic could be degraded if the Backoff timer of low-priority traffic is very small. In this case, the
traffic of the latter is high, which would not be desired. To tackle this problem, [9] proposes a black-burst (BB) contention scheme to provide absolute priority. The aim is to prioritize and minimize the delay of real-time traffic. This algorithm is applied only by nodes transporting real-time traffic. However, a BB contention does not deal with the exposed/hidden node problems.

In [12], the authors investigated the trade off between throughput and fairness. They proposed a busy tone priority scheduling model to manage multihop networks. Two narrowband busy tone signals are used to inform the two-hops-neighbors. Unfortunately, the algorithm generates a large overhead traffic and can only classify the traffic into two access categories, while the WMNs require more than two classes.

Xu and Saadwi [5] showed that the fairness problem is caused by the exposed and hidden nodes in the case of a multihop chain topology.

3. FAIR CAPACITY IN WMNS

We have made some extensions to the IEEE802.11e standard, and to simplify our process, we have supposed that:

1. All WMN nodes have the same transmission range; we fixed this distance at 250 m.
2. All packets have the same size to simplify computing and environment complexity.
3. Maximal and minimal throughputs are uniform for each transmission category on all WMN nodes. Using these parameters, nodes can ‘interact’ with each other.

3.1. Extensions made to the MAC layer

Our work is based on the use of token buckets. This tool was used to regulate TCP/IP traffic and we are going to show that combining token buckets with other mechanisms would allow us to obtain a sophisticated fairness strategy. Each access category contains a specific token bucket that can be configured differently.

First, when a node aims to transmit packets, incoming token ratio takes its maximal value (the maximal category throughput). This ratio is adjusted every \( \delta_{update} \) seconds according to a list of rules which will be presented later.

Token bucket configuration concerns principally the arrival token rate, \( 'token_rate[]' \) and the maximal bucket size \( 'nb_token_limit[]' \); the maximal and minimal token rate are represented respectively by \( 'max_token_rate[]' \) and \( 'min_token_rate[]' \). Each token is used to send only one data packet. Packets in a specified access category will not be served if there is no token corresponding to this access category. When a collision occurs, the sender must use another token to retransmit the packet again.

Token buckets are considered as an efficient mechanism to regulate traffic by affecting a low arrival token rate to nodes with higher communication probability, and a high arrival token rate to nodes with lower probability. By applying this method, an equilibrium state could be observed. Token rate adjustment is done periodically because, in one hand, token rate in the preceding state could be a transitory rate, and on the other hand, to adapt the WMNs to new topology changes.

The adjustment will be continued until the packet transmission rate among all MWN nodes is uniformed. In this case, we obtain a given configuration that represents an optimum reached dynamically by different nodes. To generalize the solution and avoid a local optimum, we have added rules by allowing a node to share the same bandwidth with its neighbors and increase its arrival token. This rule leads nodes to provide a higher global network throughput and be in a steady state.

The second extension focuses on the use of ‘duration’ field in the MAC layer. This is composed of four frames of four bits long each. In our solution we used only four bits to lead to fairness. The other subfields will be used in our future work to support a robust QoS with
weighted fairness capabilities. The used field in this work is called \textit{Uratio}. It contains the bandwidth used ratio value for a given node. It is computed according to the maximal allowed throughput (for all access categories at this moment) and transmitted within each frame. It is readjusted every ‘\textit{delta_update}’ second. This subfield is very important in our work; it allows nodes to recognize the bandwidth ratio used by each transmitter node, and it serves to readjust token arrival rates.

In the original IEEE802.11e, when a node fails to deliver a frame because of collisions, Backoff value is increased. In our work, we eliminated this mechanism and fixed the Backoff value to the initial one used in the standard IEEE802.11e.

Token is a type of delay. Its use replaces efficiently the use of delay and leads to the robustness and auto-stability of our solution.

We introduce two counters. The first one determines the number of transmitted frames each \textit{delta_update} seconds, and the second counter is used to evaluate lost frames in the same \textit{delta_update}. Note that each AC uses its own counters.

Our work supports fairness per node. However, the algorithmic structure integrated in this work allows us to support fairness per AC. In each update period, a node computes the number of total transmitted frames during the last \textit{delta_update}. The excitation level is computed according to the total transmitted frames as follows:

\[
\text{exc} = (\text{MaxQ} \times \text{max Valdelta} - \text{update}) \times \sum_{i=1}^{\text{MaxQ}} \frac{\text{nbtrpkt}[i]}{\sum_{i=1}^{\text{MaxQ}} \text{Max} - \text{token} - \text{rate}[i]}
\]

Where:

- \textit{MaxQ}: AC Number.
- \textit{MaxVal}: maximal precision value, we used \textit{Uratio} with 4 bits; this gives us 16 excitation levels with \textit{MaxVal} to 15.
- \textit{delta_update}: update period.
- \textit{nbtrpkt[i]}: frames transmitted successfully in the \textit{i}th AC.
- \textit{max_token_rate[i]}: maximal token arrival rate in the \textit{i}th AC.

The number of transmitted packets ‘trpkt’ is the sum of transmitted packets for each AC ‘\textit{nbtrpkt[CAi]}‘: while \textit{ACi} represents the \textit{i}th AC, we only used 15 excitation levels because of \textit{Uratio} precision. Each level represents 625% of the maximal allowed throughput.

Finally, we have modified the manner of performing the transmission. In IEEE802.11e after each successful transmission, Backoff is recalculated for other concurrent ACs for the same node. We have eliminated this mechanism so other concurrent ACs start at the last remaining time for Backoff. Simulations show that this mechanism increases the WMN throughput more than the original IEEE802.11e.

3.2. Adjustment rules

These rules are applicable in each \textit{delta_update} period. They are chosen to give an equilibrium state or a steady state characterized by a robust fairness and a maximal global throughput.
Algorithm A1:

If(number of transmitted packets + lost packet is not null)Then

Compute excitation level according to the preceding formula \( exc\_Level \).
Compute the mean neighboring excitation Level:
\[
\frac{(min\_excLevel+max\_excLevel)}{2}=NR\_exc\_Level
\]

For each Access Category(AC) Do

If( min\_excLevel is null) Then

the arrival token rate by lose\_thresh \% readjust the result if it is small
than the minimal allowed throughput(min\_token\_rate/15).

Else

If(exc\_Level<NR\_exc\_Level) Then

\[
\text{token\_rate}_{[i]}=\text{token\_rate}_{[i]}+\text{token\_rate}_{[i]}/15.
\]

Readjust the result if it’s higher than the maximal allowed
throughput for the AC to the maximal allowed throughput.

EndIf

If(exc\_Level > NR\_exc\_Level) Then

\[
\text{token\_rate}_{[i]}=\text{token\_rate}_{[i]}-\text{token\_rate}_{[i]}/15
\]

Readjust the result if it’s smaller than the minimal allowed
throughput for the AC to the minimal allowed throughput.

EndIf

EndIf

Loop

Else

If(Node has packets to send) Then

exc\_Level = 0

token arrival rate for each AC is fixed to the maximal allowed throughput
for that AC.

Else

exc\_Level = NR\_exc\_Level

EndIf

EndIf

Initialize lost packets counter, minimal excitation Level \( min\_exc\_Level = 15 \) and maximal
excitation Level \( max\_exc\_Level = 0 \).

These rules exploit \( Uratio \) sent by neighbors. When a node receives a frame, it compares its \( Uratio \)
with \( max\_exc\_Level \). If \( Uratio \) is greater than the existing value in \( max\_exc\_Level \), \( max\_exc\_Level \) takes
the new value contained in the incoming \( Uratio \). The value of \( min\_exc\_Level \) will be compared with
\( Uratio \) to keep the minimal bandwidth ratio.

4. PERFORMANCE EVALUATION

We implemented the proposed algorithm using NS2. We used Constant Bit Rate (CBR) traffic for
each AC. The used throughput was a saturation one. The rest of the simulation settings are as follows:
max_token_rate[] = 250 token/s
min_token_rate[] = 10 token/s
nb_token_limit[] = 16 tokens // maximal token number in this AC
thresh[] = 10 packets // used to set sensibility Level
delta_update = 1.5000 s
burstLim = 1 packet // used to support burst transmission mode
lose_thresh = 35%
Phy/WirelessPhy set CSThresh 3.652e-10 // limit carrier sensing at 252 m
Phy/WirelessPhy set RXThresh_ 3.652e-10

4.1. Simulation results

We performed several simulations for different topologies to analyze and show the efficiency of the proposed algorithm. Simulation results show that our solution improves the performance of the IEEE802.11e standard in terms of fairness and bandwidth stability. Knowing that increasing the number of nodes does not influence the obtained results was the reason behind using only six pairs of nodes at maximum for all our simulation.

In parallel topology the first topology is represented by a sequence of parallel pairs of mesh nodes. In this topology each transmitter can listen to its neighbors. We used one to six pairs of nodes (Figure 1).

Simulation results show that nodes situated in the middle have higher token arrival rates than other nodes in the extremities. Degradation in token arrival rate from the middle to extremities takes a nonlinear form rather than an exponential one. The obtained result is reasonable because nodes in the middle suffer from bandwidth availability. Therefore, they are obliged to increase their token arrival rate to enhance their communication probability. Moreover, probabilities to communicate in a given instance $d_t$ are represented in some geometric forms. The appearance of this phenomenon is due to the applied rules that insure stability to the WMN.

We can compare performances of the proposed algorithm with the IEEE802.11e standard by examining the total mean of transmitted packets and the standard deviations. The latter presents an important parameter to define fairness and robustness of the algorithm. Therefore, when WMN nodes are in an unfair state, the standard deviation takes a great value, because communication probabilities of nodes are unequal. Hence, dispersions from the total mean of transmitted packets are very significant. However, when WMN nodes are in a fairness state, the communication probabilities of the nodes are equal and dispersions are nonexistent. Obtained results are depicted in Figure 2.

Simulations show that for one pair of nodes the proposed algorithm ensures a higher throughput than the IEEE802.11e because we disabled the Backoff mechanism using instead the initial values of the standard. For four pairs of nodes the standard deviation for IEEE802.11e is equal to the total packet number which signifies that IEEE802.11e performances are worse, leading to network segmentation.

Figure 1. Parallel topology.
We examined another complicated case to study the robustness and limits of our solution in comparison with the IEEE802.11e standard. We used the same parallel topology within each node to listen to its four neighbors (two on the left and two on the right) to increase interferences and concurrences. Therefore, the total packet number mean is divided by two for each node. Results show that our solution preserves linearity. It is well known that a linear system can simply be examined to determine its limits. Total packet number mean is stabilized after we used three pairs of nodes with traffic of 10 000 packets during 300 s, as shown in Figure 3; this means that the proposed solution can guarantee bandwidth and auto-stability with convergence of the standard deviation.

However, the total transmitted packet number mean in the IEEE802.11e is not steady. The standard deviation increases in an unpredictable fashion caused by a network permanent segmentation in which a number of nodes are excluded from communication. We can approximately count the number of segments by dividing the standard deviation by the total mean.

The graphs depicted in Figures 4 and 5 represent the number of transmitted packets by each node every 6 s. We used the parallel topology. Figure 4 shows a case with four pairs of nodes and Figure 5 shows another case with three pairs of parallel nodes.

We can easily distinguish that spontaneous variations decrease from one instant to another, shown by deadened sinusoidal graphs that indeed enhance our arguments to a great extent for fairness and auto-stability of the proposed solution. Results in Figure 4 show the convergence of instantaneous transmitted packets to 67 packets/s and to 75 packets/s for Figure 5. We show that node 4 has a
nonexistent throughput and after a period it will have the same throughput as other nodes. This result shows that the proposed algorithm converges to a fair state in a short time of less than 35 s which signifies that our solution supports mobile architectures.

4.2. Exposed node

The IEEE802.11e proposes a fixed priority between traffic categories that is obtained by AIFS, Backoff periods, and the level of TxOP. This configuration may increase risks of unfairness. To address this issue, we did several simulations based on a topology composed of three parallel nodes such as the communication between central nodes supports Best Effort traffic between nodes 2 and 3. The two other pairs of nodes at the extremity of the topology have a high priority traffic generated by node 0 to 1 and a medium priority traffic from node 4 to 5. We performed simulations to illustrate this problem and compared results to the proposed algorithm. In Figure 6(a), because of the unfairness of the medium, the probability of Best Effort traffic in standard IEEE802.11e is less than the proposed algorithm as shown in Figure 6(b). We observe that the proposed algorithm converges to a fair state in a short time. Also, it can regulate all traffic and ensure that all nodes can communicate with the others.
4.3. Hidden node

A hidden terminal case is characterized by a considerable rate loss of transmitted packets. We address this issue by comparing the performance of our work with the normalized IEEE802.11e.

In this section, we study the impact of the hidden terminal. In this scenario, nodes 0 and 2 are fully independent. The aim is to prove that the proposed protocol can solve the hidden terminal problem without using RTS/CTS.

Simulation results using IEEE802.11e without RTS/CTS are indicated in Figure 7. We show that node 2 monopolizes the transmission medium after a short time. Node 0 loses access to the medium and cannot send any packet after 30 s. The problem is that the number of collisions increases the contention window size, and therefore reduces the throughput of the node 0. However, with the proposed algorithm using adjustment rules, nodes cannot monopolize the medium. A node in a hidden case announces its excitation Level \( NR_{exc\_Level} \) to its neighbors. Hence, a node possessing an \( NR_{exc\_Level} \) greater than \( NR_{exc\_Level} \) mean decreases its \( NR_{exc\_Level} \) and vice versa for the other nodes according to the preceding formula. This process converges after a short moment and leads nodes to be in fairness.

We can see that the proposed protocol is fair with respect to IEEE802.11e, and it can ensure via their adjustment rules that all nodes can access the transmission medium at any time.

We notice that the bandwidth decreases after 25 s then after 250 s. We observe that at these times collisions are higher than 35% \( \text{lose}_\text{thresh} \). Using the adjustment rules, nodes decrease their token.
arrival rate to avoid synchronous transmissions. We observe that the aggregated throughput is 241 packets/s, whereas the maximal aggregated rate experienced by a node in this case is 200 packets/s.

These simulation results show us that the proposed protocol provides a really good fairness and efficiency trade-off compared to IEEE 802.11e.

4.4. Chain topology

The chain topology is one of the most interesting, because in wireless mesh networks nodes forward data from a source to a destination node across other nodes. This situation is most common in this case and it is so important. Therefore, we used a topology consisting of four hops in which CBR traffic of 50 packets/s for each access category is used. This gives a total throughput of 200 packets/s for each node.

The simulation results are shown in Figure 8. We observe that the transmitting node 0 sends data flow more than others do, while all other nodes in the path forward at the same rate. This means that the proposed algorithm allows traffic control to be sent across the path to the destination and regulates routing traffic. We also observed that through this topology dropped packets between other nodes except the sender do not affect the dependency relationship established between the different nodes of the path.
5. CONCLUSION

In this paper, we addressed the fairness over the IEEE802.11e. We have focused on guaranteeing QoS for heterogeneous traffic types. The proposed algorithm is based on a self-configuration paradigm that allows WMN nodes to cooperate with each other to equitably share the medium. The proposed algorithm brings a combinatorial optimization to the MAC to allow the convergence to an optimum in real time. This represents the optimum configuration with respect to arrival token rate at each mesh node for each AC. We designed this work including some mechanisms to support other techniques such as the dynamic management of prioritization of different classes of service.

Our work addresses the fairness of a social network standpoint. Each node is aware of the state of its neighbors; it shares with them the bandwidth to better support the QoS of all other nodes. In future works, we are going to compare the proposed protocol with other fair protocols such as the min–max protocol [2]. We also intend to integrate the concept of node sensitivity not only to share fairly the traffic but to be aware of the nodes that generate sensitive traffic such as audio.

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AUTHORS’ BIOGRAPHIES

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