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Improving Fairness and Utilisation in Ad Hoc Networks

Arabi, Mohamed

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University of Plymouth

Improving Fairness in Ad Hoc Networks through Collision Rate Control

Mohamed Arabi, Bogdan Ghita, Xingang Wang

Centre for Security, Communications and Network Research (CSCAN)
University of Plymouth
Plymouth
United Kingdom
{mohamed.arabi; bogdan.ghita; xingang.wang@plymouth.ac.uk}

Abstract: The 802.11 MAC protocol used in Mobile Ad Hoc Networks is designed to eliminate the hidden node problem through the use of the four way handshake RTS/CTS/DATA/ACK and to reduce packet drops due to collisions by listening to the channel before transmitting data. However, this protocol can lead to unfair channel utilisation among different flows, as some of the nodes may capture the channel for a long period and leave the rest to starve. This paper proposes a collision control algorithm aiming to improve fairness and channel utilisation in wireless networks. The algorithm monitors and polices the rate of MAC collisions among flows in order to distribute available resources across all participants. The evaluation results indicate that the proposed scheme achieve 99% fairness among the competing flows.

Keywords: IEEE 802.11, Contention window, Network Allocation Vector, Fairness

1 Introduction

The 802.11 MAC protocol was designed to provide wireless connectivity between nodes. In order for this to happen, the MAC protocol implements a Distributed Coordination Function (DCF) which employs the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Each node wishing to access the channel to transmit data senses the channel first to determine whether it is free or another node is already transmitting. If the channel is free, the wireless node captures the channel and transmits data. If the channel is busy, the node backs off transmission by a value calculated using the binary exponential back off algorithm. On the other hand, the MAC protocol has no fairness mechanism to ensure fair access to the channel among nodes. A fairness mechanism is usually implemented in Access Points (APs) where the traffic is routed for all wireless nodes. However, in Mobile Ad Hoc Networks, where there are no APs, such a mechanism does not exist as the wireless nodes themselves act as traffic routers. If the wireless nodes are within interference range of each other, access to the channel is distributed fairly among nodes. This is because when a node requests access to the channel when it is free, it sends a request to send (RTS) frame and the intermediate node replies back with a clear to send (CTS) frame. The nodes nearby i.e. in the same transmission range (250m) receive the RTS and CTS frames and defer their transmissions for a specified time duration set in the RTS and CTS frames. However, nodes outside the interference range (550m) of the current sending node cannot read the time specified in the RTS/CTS frames and therefore do not update their Network Allocation Vector (NAV). As a result, they may transmit while the initial node is still transmitting which lead to packet collisions. When a collision happens, the MAC protocol exponentially increases the contention window which in turn leads to an exponential increase in the back off time. Therefore, the more collisions a node experiences; the less chances it has to capture the channel and transmit data and vice versa. This makes the MAC protocol to always favour the last transmitting node and leave the other nodes to starve.

In this paper, the aforementioned problem is tackled and a fairness mechanism is implemented at the MAC layer in order to improve fairness in such scenarios. Simulation results validate the proposed mechanism. Section 2 presents the prior work done in the area of fairness in Mobile Ad Hoc Networks. Section 3 presents the proposed mechanism and Section 4 presents an evaluation of the proposed scheme.

2 Related Work

The problem of fair distribution of channel resources in a multi hop ad hoc wireless network has been investigated in several papers. Researchers in [XS01] show that TCP performance in ad hoc networks faces a great challenge in terms of fairness. In [Be08] and [MOM06], the authors have pointed that the 802.11 protocol does not provide good fairness in environment where multiple flows are in the same contention region which leads some TCP flows to starve. They also pointed out that the reason for such unfairness is due to the exponential increase of the contention window size (CW) after each time calculation of the back off time when a collision is detected. Therefore, nodes that have experienced collisions have to wait much longer time before they can send a request for the channel and the nodes that have not experienced collisions will have more chances accessing the channel.

In order to solve this problem, researchers in [Be08] show the weaknesses of the back off algorithm in the presence of many nodes in the same contention region. They proposed an arithmetic increase of the contention window size (CW) based on how many bits the node has sent and received during a time interval and a Fairness Index previously proposed in [Dh03]. On the other hand, researchers in [MOM06] calculate the second back off time as the product of the old back off time, its log and the time slot.

In [Li03], the authors show that 802.11 does not differentiate between frames that are sensed out of the transmission range of a node and differs it transmission by the same extended inter-frame space (EIFS) duration which results in collisions as the nodes would transmit at the same time and in turn leads to unfair bandwidth utilisation. In order to overcome this problem, they proposed an enhanced carrier sensing mechanism that calculated an EIFS duration based on the length of sensed frames.

In [LWQ03], Luqing et al proposed a solution based on controlling the queue output rate, in contrast to the previous papers where a solution was adopted at the Link layer. They showed that a large congestion window causes a TCP session to use all the bandwidth available which leads to severe unfairness among other flows. They also showed that there is a trade off between high throughput and fairness. In order to fairly prevent the TCP congestion window from reaching it maximum size and cause unfairness problem, they proposed a non-work-conserving algorithm to control the queue output rate based on transmission time, delay and a random value.

Researchers in [XB01] proposed a *max-min-per-link* fair share algorithm that indicates whether to increase or decrease the contention window in order to achieve fair bandwidth share at each node based on the amount traffic sensed in its carrier sensing range. Therefore, the maximum fairness that could be achieved is determined by severity of the contention in the wireless network [XB01].

In this section, the various techniques and mechanisms to improve fairness in mobile ad hoc networks have been presented. Providing solutions to improve fairness at the Transport layer via controlling the Maximum Transmission Unit or the TCP's congestion window do not eliminate the hidden node problem. However, providing a solution at the MAC layer seems more appropriate as the MAC protocol was designed to provide access to the wireless channel. All the provided solutions suffered from throughput reduction and the effects of the hidden node were reduced but not eliminated. In order to improve unfair bandwidth utilisation a different approach has been explored and a novel mechanism has been designed based on penalising greedy nodes according to the collision rate at the MAC layer. In the next section, the proposed scheme will be presented.

3 Proposed Scheme

The IEEE 802.11 MAC protocol is unfair in the presence of multiple flows in the same contention region. Every time a node experiences a collision, its contention window increases exponentially and each time a node successfully transmits data, the contention window decreases exponentially; therefore, the binary exponential back off scheme always favours the latest successful transmission and therefore causes unfair channel utilisation [XS01]. The nodes transmission is scheduled in the IEEE 802.11 MAC protocol using the Network Allocation Vector (NAV) [KGS02]. According to NAV, if a node senses that the channel is busy by receiving an RTS or CTS that was sent to another node, it defers its transmission by a duration set in the RTS or CTS messages and updates its NAV to schedule the transmission [YK05]. However, if for example the RTS messages were sent by nodes within transmission range of each other to nodes outside the interference range of each other, the transmission of the CTS messages cannot be scheduled and therefore collisions might occur and the duration by which the node should defer its transmission cannot be updated [KGS02], [YK05]. Therefore, in such scenarios, scheduling the transmissions cannot be possible and packet collision can occur if the nodes transmit at the same time leading to unfair channel utilisation.

In order to improve fairness in scenarios where multi flows exist, a novel algorithm called Fair Bandwidth Distribution MAC protocol (FBDMAC) has been implemented in ns-2. This algorithm is based on penalising the greedy nodes that cause unfair channel utilisation according to the number of collisions experienced and some decisions are taken to improve the overall fairness in the presence of multi flows. The FBDMAC protocol calculates a moving average of the number of collisions for the DATA, ACK, RTS, CTS, AODV, ARP packets that the node experiences at the MAC layer over a period of time individually because if the node has high DATA or ACK collision rates than it is occupying most of the bandwidth and if it has high RTS/CTS/AODV/ARP collisions than it is struggling to access the channel. If the node has higher DATA or ACK collisions than β_1 then it is over utilising the channel and should be penalised. If the node has higher collision than β_2 for the rest of the packets then it is struggling to have access to the channel and therefore the FBDMAC protocol algorithm cancels the exponential back off algorithm and retransmits the collided packet to make the node more aggressive to gain access to the channel. The thresholds β_1 and β_2 have been set to 1.0 and 0.2 respectively and these values have been chosen based on monitoring the collision rate for each packet type during the simulation of the standard MAC protocol. Also, every time a new collision occurs this moving average is recalculated in order to have an up to date network state in terms of MAC layer collisions. The moving averages for each packet type are then compared to β_1 and β_2 to decide whether to penalise the nodes by doubling its contention window and backing off transmission or to cancel the back off algorithm and retransmit collided packets. The pseudo code for the algorithm is presented in the figure below.

```
/* Terminology
PktType = DATA || ACK || AODV || RTS || CTS
Δt = 1 second
cwnd = Contention Window
BK = Back Off Algorithm
α = 100
 */

while(simulation)
do
avg[PktType]=0
if(collision)
   collisions[PktType]=0
      timer=0
      while(timer <= Δt)
           collisions[PktType] ++
end if
avg[PktType]=(avg[PktType]+(collisions[PktType]/Δt)*α)/(α+1
)
if (avg[(DATA||ACK)]>β1)
      // Node is greedy
      //Penalise – increase cwnd, start back off algorithm
      Drop(packet)
```

```
        cwnd=cwnd*2
        BK.start(cwnd)
end if
if (avg[(RTS||CTS||AODV||ARP)]>β2)
        //Node is starving
        //Reward - cancel exponential back off algorithm
        if(BK.on)
              BK.stop
        else
              send (packet)
        end if
end if
done
```

Figure 1: Pseudo-code for FBDMAC Protocol

The optimal choice of β1 and β_2 would ensure fairness among the different flows and is dependent on the number of nodes in the contention region and the number of hops to destination. The FBDMAC protocol algorithm would penalise greedy nodes and help nodes that are starving to be gain control of the channel, eventually allowing the network to reach a balanced and fair share of the channel utilisation.

4 Simulation Results and Evaluation

The FBDMAC protocol algorithm presented in the previous section has been implemented in the network simulator ns-2 to test it on the topologies presented in figures 2 and 5.

4.1 Scenario 1

In figure 2, there are three pairs of communicating nodes: (n_0;n_2), (n_1;n_3), and (n_4;n_5), where nodes n_0, n_1, n_2 are the senders and n_3, n_4, n_5 are receivers respectively. The distance between the senders and the receivers is 200 meters and the distance between the pairs is 400 meters. The positioning of the nodes is important hence the choices of 200 and 400 meters, because the transmission range is set to be 250 meters and the carrier sense range is set to be 550 meters in ns-2. Therefore, the two pairs (n_0;n_3) and (n_2;n_5) do not interfere with each others transmission. However, the middle pair (n_1;n_4) suffers interference from both pairs (n_0;n_3) and (n_2;n_5) and competes for the channel resources with both of them.

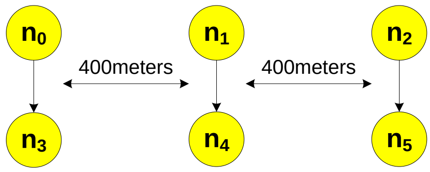

Figure 2: Three pair topology

The simulation has been run for 500 seconds, the flows start at the same time and the results for the standard 802.11 MAC protocol are shown in the graph presented in figure 3 for comparison purposes. It is clear from the graph that the throughput that the two pairs (n_0;n_3) and (n_2;n_5) achieve is very high and almost identical. However, the throughput that the middle pair (n_1;n_4) achieves is extremely low. This is because pair (n_1;n_4) competes for the channel resources with both other pairs as the pair (n_1;n_4) is in the contention region of both pairs (n_0;n_3) and (n_2;n_5).

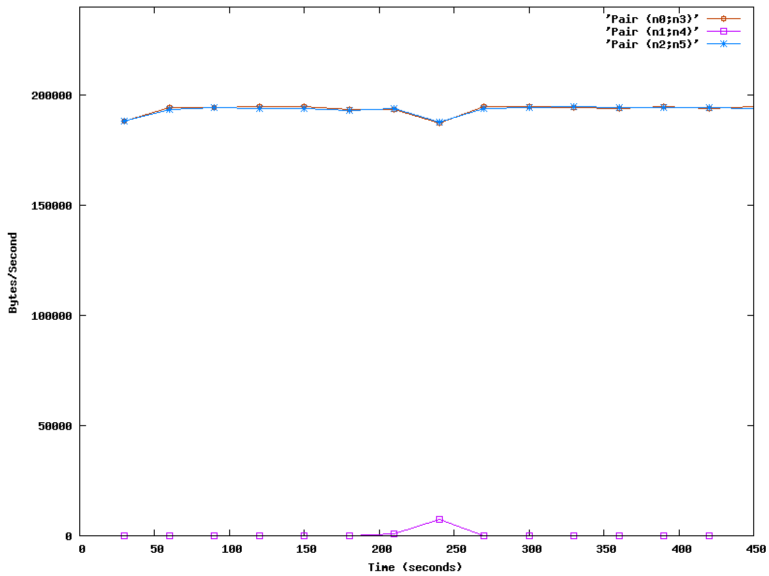

Figure 3: Throughput of three pairs. Case of Standard MAC protocol

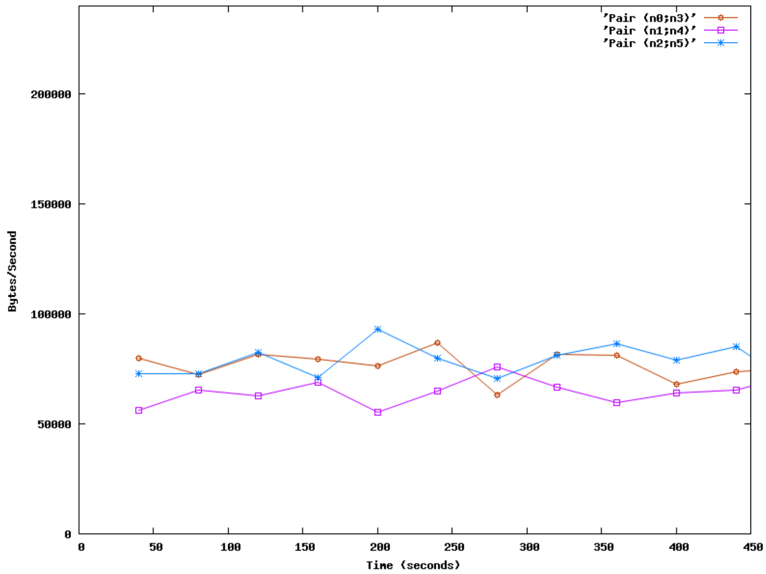

Figure 4: Throughput of three pairs. Case of FBDMAC protocol

Figure 4 shows the throughput achieved using the FBDMAC protocol. The pair (n_1;n_4) does compete with the other two pairs and achieves very satisfying throughput. In addition, by comparing figures 3 and 4, the channel bandwidth is well utilised by all the different flows fairly and much better than the channel utilisation achieved by the standard 802.11 MAC protocol.

The fairness of the proposed algorithm was evaluated using Jain's fairness equation (1/n is worst case and 1 is perfect fairness) [JCH84]:

$$Fairness = \frac{(\sum x_i)^2}{(n.\sum {x_i}^2)}$$

The average throughput achieved by each of the three flows in case of standard MAC protocol is: *(x_1; x_2; x_3) = (186086; 467; 185943) b/s*. Applying Jain's equation, the fairness achieved by the standard 802.11 protocol is 0.66. This value shows that the standard 802.11 MAC protocol does not provide fairness as the worst case for our topology is 0.33 (1/3) and perfect fairness is 1.

When applying the proposed MAC protocol on the same simulation scenario, the average throughput achieved by each of the three flows is: *(x_1; x_2; x_3) = (73237; 62019; 75477) b/s*. Applying Jain's equation using these, the networks fairness is 0.99. This value shows that the FBDMAC protocol does indeed provide almost total fairness among the different flows.

From the graphs above and by applying Jain's equation it is clear that the FBDMAC protocol achieves almost total fairness with 99% which is a great fairness improvement from that of the standard MAC protocol.

The FBDMAC protocol is designed to be adaptable to different network topologies. In the next subsection, the FBDMAC protocol will be tested on a different scenario to prove that it does adapt and improve the network's fairness when compared to the standard MAC protocol.

4.2 Scenario 2

In figure 5 below, nodes n_0, n_1 are senders and n_2, n_3 are receivers respectively. If n_0 and n_1 start transmitting at the same time and if n_0 captures the channel first, the packets sent by n_1 would be dropped due to collisions with n_0 packets. The contention window for n_1 would increase exponentially and also n_0 and n_1 would not be able to schedule their transmissions as they cannot update their NAV tables because they cannot read nor understand the RTS and CTS messages exchanged as n_2 and n_3 are outside the interference range of each other. In addition, as mentioned earlier, the MAC 802.11 favours the latest successful node as its contention window would always be small, making it even harder for n_1 to capture and utilise the channel.

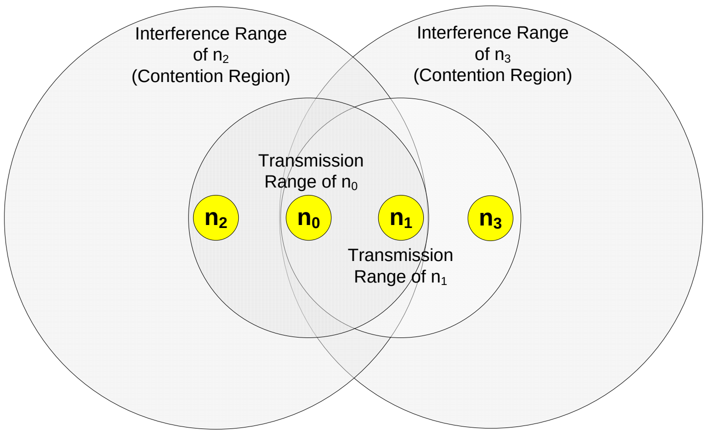

Figure 5: Two pairs Topology

The simulation has been run for 500 seconds, the nodes have been positioned to be 200 meters apart from each other and the results for the standard 802.11 protocol show that the pairs (n_0;n_2) and (n_1;n_3) achieve 75091 b/s and 107062 b/s throughput respectively; whereas the simulation results for the FBDMAC protocol show that the pairs (n_0;n_2) and (n_1;n_3) achieve 81300 b/s and 83751 b/s throughput respectively. Applying Jain's fairness index equation, the standard MAC protocol achieves 97.01% fairness and on the other hand, the FBDMAC protocol achieves 99.99% fairness. This shows that the FBDMAC protocol does improve the fair distribution of bandwidth.

Testing the FBDMAC protocol under the two different scenarios as shown in figures 2 and 5 has shown that it does provide fair access to the channel and equal bandwidth share between the competing flows. However, the overall network throughput has dropped by 43% for the scenario shown in figure 2 and by about 9% for the scenario shown in figure 5. This is due to factors such as penalising the greedy nodes to allow starving nodes to have access to the channel and to computation overhead.

5 Conclusion and Future Work

The 802.11 MAC protocol works well in scenarios where flows are in the same interference range of each other. However, if the flows are outside the transmission range but within carrier sense range unfairness problems arise. The FBDMAC protocol version has been shown to greatly improve fairness. In addition, good choices of β_1 and β_2 improve the fairness even better depending on the network's topology. On the other hand, the overall throughput drops due to penalising the greedy nodes. In future work, improving the overall throughput while maintaining fair channel access will be looked into, dynamically selecting β1 and β_2 will be investigated as the topology of a mobile Ad Hoc Network changes unpredictably over time and an algorithm that would learn about the networks topology and update the values of β1 and β_2 accordingly will be proposed. Also, how frequent should the average of the number of collision be calculated and what impact that has on fairness on one hand and on processing power consumption on the other hand. Also, the proposed scheme will be tested on multi hop flows to determine its efficiency and limitations and to propose improvements and alternatives.

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