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Analysis of TCP-unfairness from MAC Layer Perspective in Wireless Ad-hoc Networks

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Abstract

In Ad-hoc networks every single node or station takes the responsibility to forward the data packets from the nodes that lie in the range with them. This additional routing responsibility might lead to performance degradation in some cases. Moreover, it is also reported that TCP which is designed for wired networks exhibit poor performance in terms of throughput and fairness in ad-hoc networks. Attempts to alleviate this issue included solutions from both TCP and MAC layer protocol modifications. This work aims at in-depth analysis of MAC level solutions (basic 802.11, 802.11 with RTS/CTS and Collision Detection Mechanism Based-MAC) to address TCP unfairness problem in 802.11-based multi-hop networks. A set of simulation based experiments are conducted and their observations are analyzed using metrics like throughput, goodput and loss probability. The metric loss probability is taken to investigate the protocols both from the perspective of congestion and collision i.e. the impact of congestion window and contention procedure on the end-to-end performance. The results obtained from the simulation revealed the inefficiency of the CDMB-MAC in the scenarios where hidden and exposed terminals do not exist. Further when TCP congestion window is set to 1 the basic 802.11 MAC is found sufficient to provide higher throughput with better fairness among the TCP connections but when TCP congestion window size is increased to 32 the 802.11 MAC with RTS/CTS scheme gives better performance. Added to this all the three MAC protocols fail in the scenario where the source and destination of a connection lie in the transmission ranges of destination and source of other connections. Therefore it can be concluded that it is indispensable to design an adaptive MAC protocol that could provide Fairness among TCP connections in all scenarios.

Keywords: Ad-hoc, Analysis, Fairness, MAC, TCP

1. Introduction

An Ad-hoc network is formed by any set of nodes that have to communicate with each other to meet some common objectives like sharing of files, chatting, participating in games, without any fixed infrastructure. This network dynamics (frequent change in the neighbor list, transmit power, transmission range and interference range) has more influence on the path calculation. Moreover to achieve high performance in ad-hoc networks, researchers are redesigning protocols to address the problems like high packet loss probability, unfair sharing of bandwidth among competing nodes, immense energy consumption and elapsed time during data transfer[1–2].

1.1 TCP Unfairness in Ad hoc Networks

Transport Control Protocol (TCP) which exhibits good performance in terms of through put and fairness in wired network fails to achieve the same performance in wireless networks. The conflict between the assumed characteristics of TCP design and the nature of wireless networks is the major cause of this performance degradation which is also discussed in[3-5]. In wired networks the infrastructure is fixed and the packet loss is always mapped to congestion. Accordingly whenever a packet loss occurs the TCP reacts with the congestion control mechanism. However, in Ad-hoc networks there is no fixed infrastructure and the channel access is contention based. Moreover the

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packet loss is not solely due to congestion. Therefore the TCP congestion control mechanism is not suitable in such networks.

In general, TCP unfairness arises when the connections differ in terms of RTT, Congestion level and Error rate that is, a connection with low packet loss probability and small Round Trip Time (RTT) may achieve higher throughput whereas a connection with high loss probability and high RTT may achieve low throughput. In comparison to wired network, in Ad-hoc network the frequent path change, high error rate and high variation in channel access probability have yielded high variation in achieved end to end performance.

1.2 Classification of Solutions to Address the TCP Unfairness Issue

To achieve the fairness at Transport level over Ad-hoc network many solutions are proposed. Based on its nature, the existing solutions can classified into Transport level solutions[6,7], MAC Level solutions[8,9] and Cross layer solutions[10-12]. In transport level solutions, modifications to the existing transport layer have been incorporated. Even though many transport level solutions are proposed it is stated that the root cause for the unfairness in TCP is the underlying 802.11 MAC contention procedure. With this common objective Cross layer and MAC level solutions were proposed. In Cross level solutions, a co-ordination scheme between the TCP level and MAC level is used. As cross layer solutions requires modification to the protocol stack these solutions are hard to implement. In MAC level solutions modifications are incorporated only in IEEE 802.11.

The MAC level solutions are feasible to incorporate in current implementations with less effort compared to cross level solutions. Hence in this work we focused only on the analysis of TCP fairness with MAC level solutions. We have presented detailed analysis and comparison of the basic 802.11 MAC and a recent solution CDMB-MAC that proposed a MAC level modification to achieve TCP fairness[8].

2. TCP unfairness Problem from MAC Perspective

2.1 Role of MAC in Solving TCP Fairness Problem

The abstraction principle of OSI model and TCP model says that the protocols at each layer are independent of the protocols which are running the layer above and below. As per this principle, the applications which were designed using TCP can be deployed over 802.3, 802.11or 802.16. Even though TCP has been treated as physical layer independent protocol, the physical layer problems and link layer access control procedures have more impact on the achieved end to end performance. Hence the performance of TCP is dependent on the performance of 802.11 in Ad-hoc networks. It is illustrated in Figure 1.

For example in this scenario if node 2 has captured the channel for its transmission continuously that is node 1 and node 3 has failed to capture the channel, the connection between node 2 and node 4 will have higher throughput at the same time will yield low throughput for the connection between nodes 1 and 4. In this scenario the failure to transmit the packets due to contention will be considered as the packet loss due to congestion. From this discussion it can be inferred that any performance enhancements that are expected from the upper layers can be addressed only by modifying the underlying MAC protocol.

2.2 Existing MAC Multiple Access Procedures in Solving TCP Fairness Problem

Despite the fact that MAC level modification is expected to provide fairness, the level of fairness provided by basic 802.11 should not be underestimated. Since 802.11 was designed with the contention and back off procedure to provide the equal chance to access the channel, a in-depth study on TCP fairness over 802.11 is highly essential and hence it is considered in our analysis.

To avoid collision the contention procedure of 802.11 has three types of waiting times namely SIFS (Short Inter Frame Space), DIFS (Distributed Inter Frame Spacing),

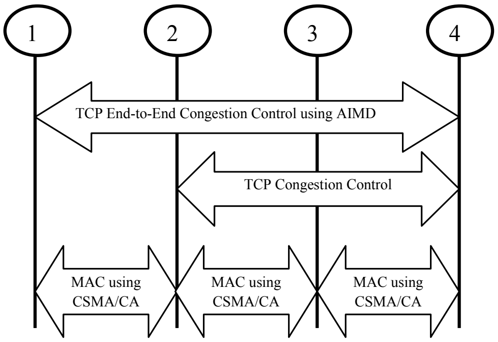


Figure 1. Depiction of TCP end-to-end Congestion control using CSMA/CA.

PIFS (Point Coordinated Function Inter Frame Space). Only when the channel is free for DIFS time a node can start its packet transmission. Similarly every time when a node has to respond with a CTS or ACK packet it has to wait for SIFS time, monitoring whether the channel is idle or not. If the channel is idle for that SIFS duration the node can transmit the packet. To provide equal chance (i.e. fairness) to all contenting nodes the "Contention Window" is initialized with a random value. Everytime if a node wants to transmit a packet it has to monitor the channel for DIFS time. As every node before transmitting a packet has to content with its neighboring nodes, the random back off algorithm was added to reschedule their channel access such that their contention periods will be distributed in next attempt.

2.3 Extended MAC to Solve TCP Fairness Problem[8]

CDMB-MAC[8] proposes a modification to the existing 802.11 MAC by incorporating changes to the RTS/CTS mechanism. As per the RTS/CTS exchange procedure the node which has a data to transmit sends a RTS packet to the receiver and then waits for CTS packet from receiver. The node which fails to receive the CTS packet will enter into back off procedure and initiate their next attempt after the back off period. The number of attempts (retry count) is restricted to 7. In CDMB-MAC the number of attempts is increased from 7 to 200. To avoid the contention at next attempt, in the scheme a probability factor is introduced and only when the probability is 0.4 the transmission of RTS packet is allowed.

In[8], the simulation was conducted with a string topology of four nodes. The maximum congestion window size used is 1 and the topology is shown in Figure 2. The authors have stated that this particular solution works fine for a string topology of 4 nodes.

2.4 Theoretical Analysis on MAC based Solutions

Fairness from a user point of view means if two connections exist in a network their bandwidth sharing should be equal. However if nodes are in different transmission/Interference range then there need not be equal share of bandwidth. So, fairness has to be considered only when there is a sharing of link or set of links by two connections. Therefore the algorithm to address the fairness issue should not only compare the performance with the throughput obtained. Instead the algorithm should be discussed based on aspects like fairness, path to reach destination, Interference and transmission ranges.

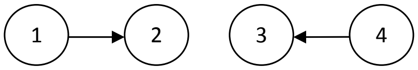


Figure 2. String Topology of four nodes with two TCP connections.

If 802.11 MAC is incorporated at MAC level and the nodes in the network lie in interference range with each other, then through physical sensing the nodes will learn about the presence of packet transmission in the network. In such cases if RTS/CTS mechanism is not used the time spent for exchange of control packets is saved and higher throughput can be obtained.

In case if Hidden nodes exists in the network then meager physical sensing will not be helpful so the use of virtual carrier sensing mechanism can avoid collisions among nodes. However back off mechanism of virtual carrier sensing will delay next attempt to access a channel. Though 802.11 without RTS /CTS lead to collision, the time spent for exchange of control packets can be saved and can be converted into useful packet transmission. Moreover the underutilization of the channel due to contention and exchange of control packets can be avoided and higher throughput can be obtained in spite of collisions.

In[8] the authors claim that by increasing the RTS retry count and introducing a probability parameter that is checked every time when a RTS packet has to be sent would provide an increased fairness and throughput among TCP connections. However the increased retry count will contribute to additional congestion in the network as the nodes persists to involve in contention until the increased retry count is reached thereby leading to wastage of bandwidth and will yield very low throughput than estimated. Although CDMB-MAC provided fairness in some cases the reduced throughput rates makes it an unacceptable MAC protocol that can be employed to all environments in Ad-hoc networks.

3. Performance Analyses of MAC Solutions in Solving TCP Unfairness Problem

For the purpose of Simulation three topologies with varying Transmission and interference ranges are considered. Simulations to depict the significance of buffer size and window size are also conducted and the results are summarized in this section.

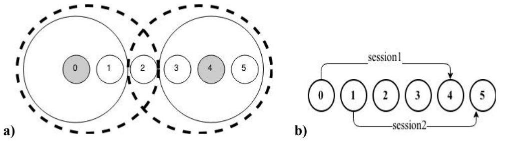
3.1 Topology-1: Two Sessions with Overlapping Paths

The experiment with this topology has been conducted to analyze the behavior of the nodes in accessing the channel at MAC level, the significance of RTS/CTS mechanism and achieving fairness at TCP level.

As shown in Figure 3 six nodes which are 200 m apart from each other with transmission range of 250 meters and interference range of 550 meters are considered for simulation. Hence a node can only sense and transmit packets to the node which is one-hop away from it. A TCP connection between node 1 and node 5 and another TCP connection between node 0 and node 4 are compared. The source and destination pairs are selected in such a way that they lie far away from each other. Both the sessions are initiated at same time and the simulation runs for 200 seconds. The timeline diagram for the throughput obtained for connections with overlapping path in 802.11 MAC with RTS/CTS is shown in Figure 4 and the average throughput obtained for three solutions are shown in Figure 5. Jain's Fairness Index is used to measure the fairness among the TCP connections. Due to space constrain the timeline for only few connections are shown.

It is observed that for the above topology the throughput obtained when the RTS/CTS mechanism is disabled is higher when compared to the throughput obtained with the RTS/CTS mechanism and the modified MAC Protocol.

It is also observed that the basic 802.11 with RTS/CTS mechanism does not provide fairness among the two TCP connections. The reason behind the unfairness is the back off mechanism used which doubles the contention window size for the node that failed to access the channel in the first attempt so next attempt for the connection is delayed and the connection which won the for first time will always capture the channel and have higher throughput as mentioned in[8]. Though CDMB-MAC provides fairness among the two connections provides very low throughput when compared to 802.11 MAC without RTS/CTS. Since the nodes are not spending time for exchange of RTS/CTS frame compared to the other mechanisms, the basic 802.11 MAC without RTS/CTS exchange will achieve higher throughput.



c)

Node'sPosition	0	1	2	3	4	5
<X,Y>	<100,200>	(300,200)	<500,200>	<700,200>	<900,200>	<1100,200>

Figure 3. **(a)** Depiction of Topology 1 with transmission and interface range **(b)** Connections between the nodes and **(c)** Physical positions of the nodes.

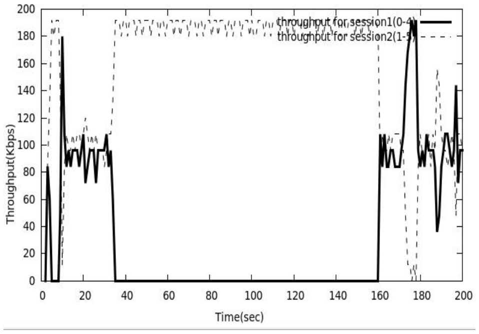


Figure 4. Throughput for the connections with Overlapping Path in 802.11 MAC with RTS/CTS.

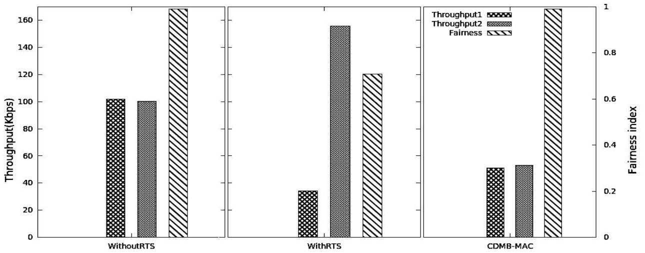
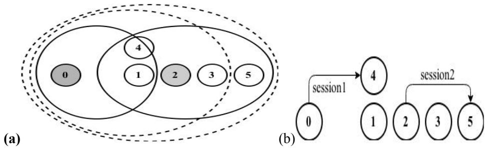


Figure 5. Average Throughput and Fairness Index for TCP connections with overlapping path.

It can be concluded from this simulation that situations when two sessions with overlapping paths are initiated simultaneously the basic MAC is sufficient to provide better fairness and throughput. The use of any other MAC protocol may degrade the performance.

3.2 Topology-2: Two Sessions with Independent Path

As shown in Figure 6(b) TCP connections between node 0 and node 4 and a TCP session between node 2 and node 5 are compared. Both the sessions take independent paths to reach their destination but the nodes 1 and 2 lie in range with each other.



(c)

Nodes Position	0	1	2	3	4	5
<X,Y>	<100,200>	<300,200>	<400,200>	<500,200>	<300,300>	<600,200>

Figure 6. **(a)** Depiction of Topology 2 with transmission and interface range **(b)** Connections between the nodes and **(c)** Physical positions of the nodes.

The average throughput obtained is shown in Figure 7. As mentioned in the earlier scenario from the results it is evident that the basic MAC without RTS yields better performance in terms of throughput, similarly though the same fairness index is obtained in the other two cases throughput rates significantly gets lowered due to exchange of control packets.

Moreover analysis from the trace file revealed that the packets from node 0 directly reaches node 4 without crossing node 1.So node 2 which is the other source is free to transmit the packets with having to participate in contention. Hence both sessions have equal throughputs.

3.3 Topology-3: Two Sessions with Independent Path with the Source and Destination Pairs are Separated by Equal Distance

In Figure 8 a TCP connection between node 0 and node 4 and a TCP connection between node 2 and node 5 is compared. Both the sessions take independent paths to reach their destination but the nodes 1 and 2 lie in range with each other. This scenario is different from scenario (2) in the fact that the source and destination pairs of both the sessions are separated by equal distance. For better visualization the throughput for granularity 1 second is shown in Figure 9 and the Average throughput and fairness is shown in Figure 10.

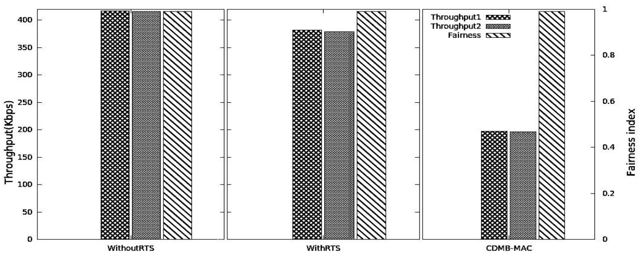
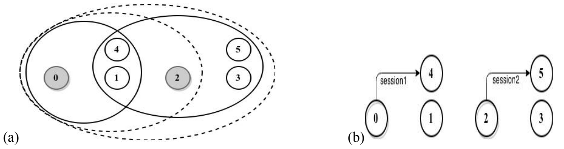


Figure 7. Average Throughput and Fairness Index for TCP connections with independent path (unequal distance between source and destination).



c)

Nodes Position	0	1	2	3	4	5
<X,Y>	<100,200>	<300,200>	<500,200>	<700,200>	<300,300>	<700,200>

Figure 8. **(a)** Depiction of Topology 3 with transmission and interface range **(b)** Connections between the nodes and **(c)** Physical positions of the nodes.

It is clearly observed in Figure 10 that there is a remarkable difference in the throughput obtained and the fairness obtained in this case as node 1 and 2 have to contend with each other every time to capture the channel and all the three MAC protocols fail to provide fairness.

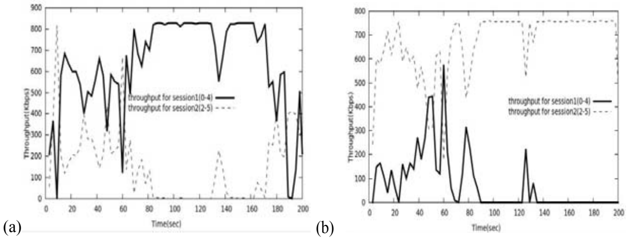


Figure 9. **(a)** Throughput of "802.11 MAC without RTS/CTS" for connections with different path and equal distance between source and destination and **(b)** Throughput of "802.11 MAC with RTS/CTS" for connections with different path and equal distance between source and destination.

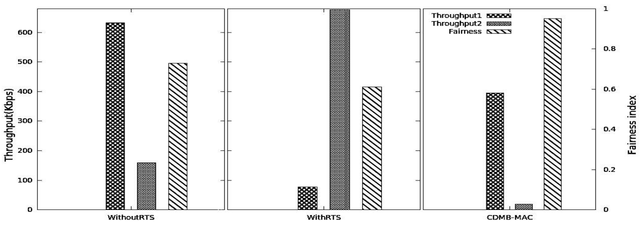
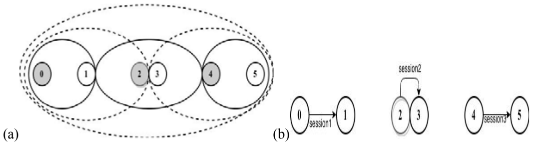


Figure 10. Average Throughput and Fairness of Two connection with Independent path with equal distance between source and destination

3.4. Topology-4: Three Connections with Sources and Destinations Out of Range from Each Other

In Figure 11 Three TCP sessions between nodes 0 and 1, 2 and 3, 4 and 5 respectively are compared. All the nodes are 200 meters apart and so no two sources lie in the same transmission range with each other.

The Throughput for three TCP connections with CDMB-MAC where source and destination pairs out of range from each other is shown in Figure 12 and the average throughput for three TCP connections with the three different MAC protocols considered is shown in Figure 13. In this particular scenario the throughput for first and third session are equal but the second session is always very low because of the fact that the source and destination nodes of session 2, node2 and node 3 respectively lie in range with either source or destination of other sessions, so always there is a channel contention before any node transmitting packets and always node 2 is suppressed from acquiring the channel. All three protocols considered for comparison failed in this particular case to resolve the unfairness between the connections.



(c)

Nodes Position	0	1	2	3	4	5
<X,Y>	<100,200>	<300,200>	<500,200>	<650,200>	<900,200>	<1100,200>

Figure 11. **(a)** Depiction of Topology 4 with transmission and interface range **(b)** Connections between the nodes and **(c)** Physical positions of the nodes.

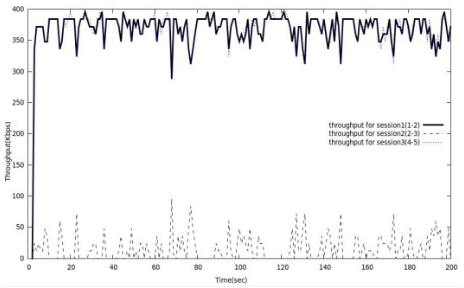


Figure 12. Throughput for three TCP connections with CDMB-MAC where source and destination pairs out of range from each other.

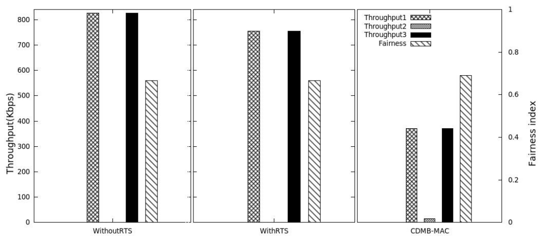


Figure 13. Average throughput and fairness index for connections with source and destination pair out of range from each other.

It can be noted from Figure 13 that the average throughput of TCP connection 2 (from node 2 to 3) is almost nil in all cases. Also when CDMB-MAC is used the throughput rate gets lower while achieving same fairness rate.

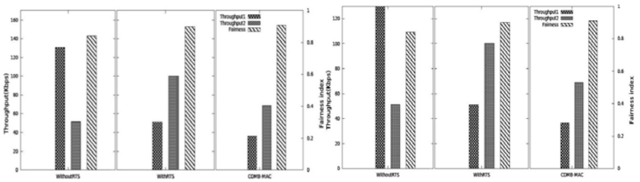
It is mentioned in the theory that the change in the TCP congestion window will have small effects on the throughput obtained, but the following simulation scenarios and results obtained reveals that the change in window size will have an remarkable effect in the network.

4. Effect of Different Buffer and Window Size

The purpose of this experiment is to analyze the significance of window size and buffer size over the end-to-end performance (throughput, goodput and fairness). Two experiments were conducted for different buffer sizes and the observations are tabulated

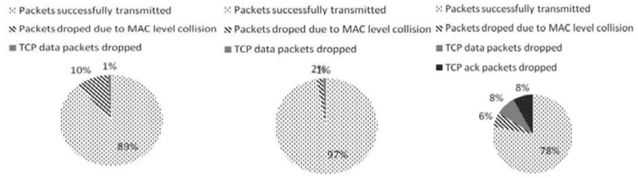
From the analysis we observed that window size of 32 has achieved comparatively low end-to-end performance. This has been verified using throughput and fairness metrics. There are few exceptions to this common observation. The CDMB-MAC has same aggregate throughput when the window size was increased however does not provide fairness which is its major aim.

From the Figure 5 and 14 (a) and (b) it is observed that when the TCP congestion window =1 and Buffer size=20, the fairness is always high except in the case of MAC with RTS. When the TCP congestion window =32 and Buffer size=20, it is observed that the fairness between the connections is comparatively low. When the TCP congestion window =32 and Buffer size=50, though 802.11 without RTS/CTS provides higher throughput, there is unfairness among the connections. When the TCP congestion window=32 and Buffer size=20, the drop rate is comparatively low as depicted in the Figure 15.When the TCP congestion window=32 and Buffer size=50, the drop rate is high as shown in Figure 16, and the MAC with RTS/CTS performs better with minimum drop rate.



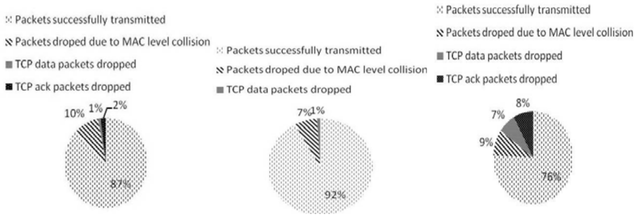
(a) (b)

Figure 14. **(a)** Average throughput and Fairness when Congestion Window=32 and buffer size =2 and **(b)** Average throughput and fairness when Congestion Window=32 and buffer size =20.



(a) (b) (c)

Figure 15. **(a)** Drop rate for "Without RTS" when CWND=1 **(b)** Drop rate for "With RTS" when CWND=1 and **(c)** Drop rate for "CDMB-MAC" when CWND=1.



(a) (b) (c)

Figure 16. **(a)** Drop rate for "Without RTS" when CWND=32 **(b)** Drop rate for "With RTS" when CWND=32 and **(c)** Drop rate for "CDMB-MAC" when CWND=32.

Furthermore it is observed that in case of MAC without RTS/CTS and MAC with RTS/CTS "collision" is the major cause for drop but with CDMB-MAC the drop is due to collision, TCP and ACK packets. It can be concluded that the increase in the window size, leads to decline in performance and also affects the fairness.

5. Performance Analysis Summary

From the analysis with various topologies it is observed that each scheme gives high end-to-end performance in terms of throughput and fairness in some scenario and suffers degradation in other scenarios. Based on the results from the simulations conducted suggestion of the MAC protocol that can be used for a given scenario is given as recommendations in Table 1. It is also evident that the increased retry count mechanism of CDMB-MAC contributes to achieve the fairness among the flows with acceptable throughput in some cases but fails to achieve the tradeoff between throughput and fairness in some scenarios. It is also observed that none of the schemes are suitable for all possible scenarios that prevail in Ad hoc networks.

Table 1. Recommendations of the MAC protocol to achieve end-to-end fairness

Topology	Recommended MAC Scheme	Throughput	Fairness
Topologies with Buffer size=20, Congestion Window =1			
Connections with overlapping path with Buffer size=20 and CWND=1	MAC Without RTS	High	High
Connections with different path with Buffer size=20 and TCP CWND=1	MAC Without RTS	High	High
Connections with source out of range from each other path with Buffer size=20 and TCP CWND=1	None(All three MAC solutions fail to achieve fairness)	–	–
Topologies with varying buffer size and Congestion Window =32			
Connections with overlapping path with Buffer=20 and TCP CWND=32	MAC With RTS	Medium	Medium
Connections with different path with Buffer=50 and TCP CWND=32	MAC With RTS	Low	High

6. Conclusion

In this analysis we have focused on the fairness aspect of TCP in Ad-hoc networks from MAC perspective. It is evident from the results that the underlying MAC protocol affects the throughput and fairness obtained in any given scenario. Furthermore it is observed that the solutions proposed to address the TCP Unfairness in ad-hoc networks are not conductive in all cases. Therefore to achieve high end to end performance, a design of an adaptive multiple access procedure is an important requirement to next generation Ad-hoc network.

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