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Performance Evaluation of MAC for IEEE 802.11 and LAA LTE

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Abstract— The considerable amount of underutilized spectrum in the unlicensed band has motivated 3GPP to study the introduction of LTE in the ISM band to fulfill its increasing demand for extra bandwidth. This will make LTE and Wi-Fi the main opponents in the ISM band. This paper presents the system performance analysis of MAC for LTE and a comparative study to Wi-Fi. Extensive MAC systems simulations are performed under various scenarios and with different parameters. The results show a better efficiency of channel access of Wi-Fi under high competition. Performance of LBT-based LTE MAC is dramatically affected by changing parameters while the performance of Wi-Fi MAC is sustained.

Index Terms—LBT LTE; Wi-Fi; Throughput Efficiency

I. INTRODUCTION

Currently, the increasing demand for extra bandwidth in the Long term evolution (LTE) technology to fulfill the high data rate demanding services is attracting plentiful researchers. To introduce this issue, the adoption of Industrial-Scientific-Medical (ISM) band in line of making LTE and Wireless fidelity (Wi-Fi)-based technologies co-exist in the 5 GHz band is studied by 3rd Generation Partnership Project (3GPP) [1].

Presently, the ISM band accommodates 802.11 (Wi-Fi and Bluetooth) and 802.15.4 (ZigBee) within 2.4 GHz and Unlicensed national information infrastructure (U-NII) in 5 GHZ bands. Besides, LTE wireless technologies operate in the licensed band as the major target is to maximize the spectral efficiency and optimize the user experience. As a consequence of these highly-demanding wide spectrum band services, 3GPP studies allowing licensed access technologies to be hosted in the unlicensed band. This requires careful design as it may completely block Wi-Fi based access networks operating in unlicensed band and favor Licensed Assistance Access (LAA)-based access technologies [2].

Wi-Fi is designed to function in the unlicensed band as it uses a contention-based algorithm to mitigate interferences with other Wi-Fi access technologies, either from the same or different operators. Since Wi-Fi and LTE are originally designed to operate in different bands [3], the coexistence of both systems cannot be achieved without making core changes in their standards. Hence, 3GPP initiates the "Listen Before Talk" (LBT) mechanism [4] to allow LAA to coexist with other systems operating in the 5GHz band. This LBT mechanism includes Load based equipment (LBE) and Frame based equipment (FBE) which are designed to compete with Wi-Fi access mechanism for accessing the channel [5].

In this paper, the differences between LBT-based LAA LTE and Wi-Fi system performances in accessing the channel are explored. This comparison is done regarding the Medium access control (MAC) of both systems. The paper is structured as follows. In section II the related work is briefly reviewed. In section III the methodology and the proposed method for modeling LBE-based LBT and Carrier sense multiple access with collision avoidance (CSMA/CA) are discussed in detail. Section IV represents the results of the proposed models and discusses the differences between them. The last section gives concluding remarks and future work.

II. RELATED WORK

The adoption of unlicensed band to LTE has recently attracted many researchers. In [6] the authors evaluate the performance of the coexistence of Wi-Fi and LTE without LBT in unlicensed band, focusing on the fairness of the channel access. The LTE performance is not affected by the presence of Wi-Fi while the second degrades. Reaching the same results, [7] proposes that LTE benefits from the idle back-off times of Wi-Fi. Hence, the Wi-Fi efficiency is sustained and the bandwidth utilization efficiency increases. Authors in [8] proposes is blanking some frames of LTE to support Wi-Fi to fairly coexist with LTE. In [9], the authors support the LTE operation in unlicensed band aiming to encourage the approach of the 5th Generation (5G). The authors of [1] after showing the severe effect by LTE on Wi-Fi, they discussed how Wi-Fi can benefit from the transmit power control or the blank sub-frames in LTE. In [2], the interference avoidance issue is presented to increase the capacity of small cell networks in unlicensed spectrum without affecting the performance of Wi-Fi. The authors of [10] consider whether it is more beneficial to use the LBT algorithm or treat interference as noise in the channel.

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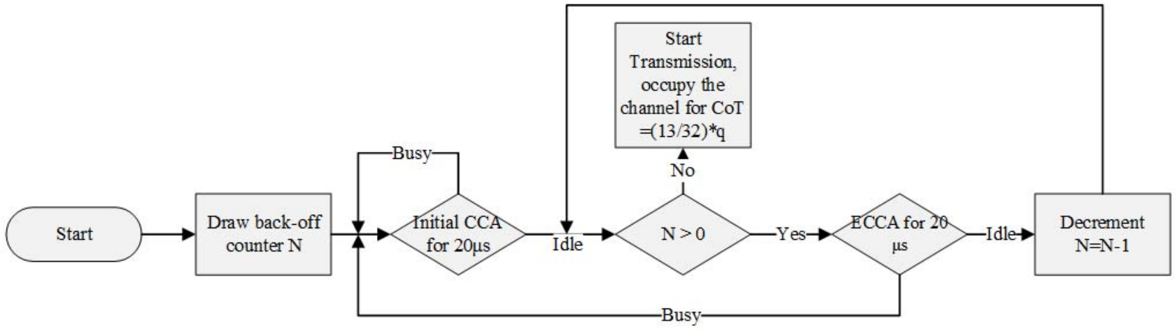


Fig. 1 LBE Process flowchart [11]

III. PROPOSED MODELING OF MAC IN WIFI AND LBE-LTE

First of all, the algorithms of CSMA/CA and LBE-based LBT are modelled as a state diagram showing different functions to be implemented for MAC. Different numbers of LAA nodes and Wi-Fi nodes compete to access one channel to record the performance of both LBE-based LBT and CSMA/CA.

The flowchart shown in ***Fig. 1*** illustrates the LBE-based LBT algorithm with Extended clear channel assessment (ECCA) procedure [11].

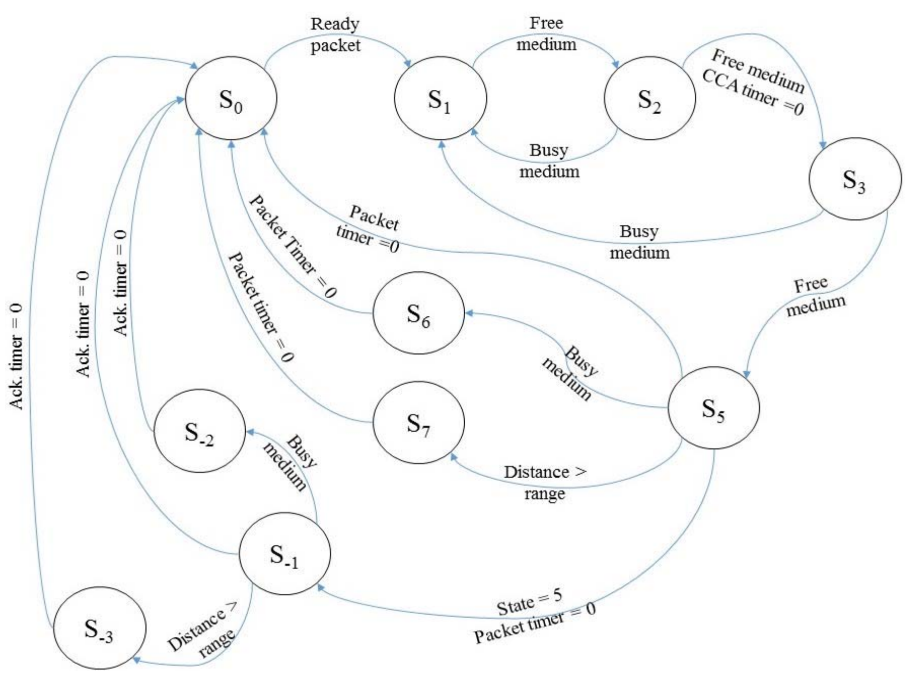
Initially, the random back-off counter (N) is selected N ϵ [1, q] where q takes a positive integer value ranging from 4 to 32. An initial Clear channel assessment (CCA) check is then applied for 20 microseconds (µs). If the channel is idle, the counter N is tested. If it has a value of 0, transmission starts and the channel becomes occupied. For the nodes of LBE-based LBT, the channel is occupied for an adaptive time defined as "Channel occupancy time" (CoT) that indicates the size of frame transmitted. The CoT is calculated according to equation 1.

$$CoT = 13 * \frac{q}{32}\ ms. \qquad (1)$$

After occupying the channel, the process returns and restarts with a new counter N.

However, if the counter has a value greater than 0, the process is continued by applying ECCA for 20 µs. If found to be successful, the counter N is decremented by 1 and the process goes back to test if the counter reaches 0 or not to start another transmission. If however ECCA failed, the process checks the idleness of the channel again by repeating initial CCA and repeating the subsequent steps until the packet is successfully transmitted. Consequently, the Contention window (CW) for LBE-based LBT depends on N. The time slot is fixed to 20 µs and CW is accordingly N×20µs.

The state diagram shown in ***Fig. 2*** is a proposed method for modeling LBE-based LBT with ECCA procedure [5].



System States	
S_0	Idle state
S_1	Channel sensing
S_2	CCA timer (20 µs)
S_3	ECCA (N x 20 µs)
S_5	Sending frame
S_6	Packet collision
S_7	Unreachable packet
S_{-1}	Sending ack.
S_{-2}	Ack. Collision
S_{-3}	Unreachable ack.

Fig. 2 Proposed LBE-based LBT state diagram

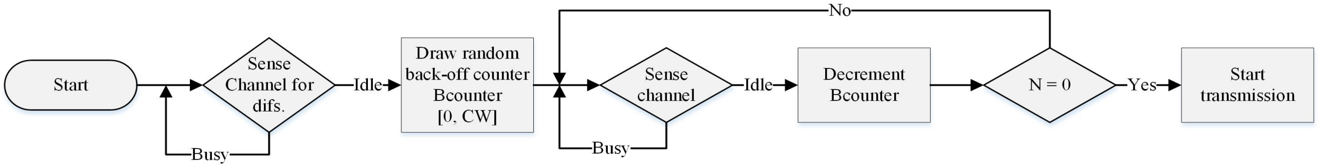


Fig. 3 CSMA/CA process flowchart [12]

The proposed method for modeling LBE-based LBT algorithm is divided into 3 main stages: Channel sensing, packet sending and acknowledgment sending.

A. Stage 1: LBE-based LBT Channel Sensing

The first stage includes the first 4 states in ***Fig. 2***. The node remains in state S_0 until the packet is ready to be sent. Once ready, the node proceeds to state S_1 where the channel is initially sensed. The procedure to state S_2 happens only when the channel is free. CCA is applied for 20 µs. If the channel is busy during the CCA period, the node returns back to state S_1. If it is free, the node proceeds to state S_3. There, ECCA is applied for 20 µs. N is decreased by 1 after every successful ECCA until it reaches a value of 0. If the channel is busy at any time during this stage, the node returns back to state S_1. The packet sending stage is started by proceeding to state S_5 when N=0.

B. Stage 2: LBE-based LBT Packet Sending

State S_5 denotes the start of the packet transmission for the length of the packet. If the channel is at any time busy, state S_6 is proceeded to and the packet is considered lost to collision. If the distance between the source and the destination is greater than the range of the node, state S_7 is proceeded to and the packet is considered unreachable. Only in the case of a free medium and a distance staying within the range during the whole packet length, the packet transmission is considered successful.

C. Stage 3: LBE-based LBT Acknowledgment Sending

When state S_5 reports a successful transmission, state S_{-1} is reached. This state denotes the acknowledgment sending from the destination to the source. If the channel is busy at any time during the whole duration of the acknowledgment, the acknowledgment collides and state S_{-2} is reached. State S_{-3} is proceeded to if the distance between the destination and the source exceeds the range of the channel. The acknowledgment is then unreachable. Only in the case of a free medium and a distance staying within the range during the whole packet length, the acknowledgment transmission is successful.

The flowchart shown in ***Fig. 3*** illustrates the CSMA/CA algorithm that uses a back-off method with a random back-off counter (Bcounter) selected ranging from 0 to CW-1. CW ranges from 8 to 1024. At the start of each packet transmission each node sets the CW to CW_{min} and accordingly the value of Bcounter is chosen. After each unsuccessful packet-transmission CW is doubled with a maximum value to reach of CW_{max} [13]. Initially, if the channel is idle for Distributed inter frame space (DIFS), the Bcounter is drawn. If after that the channel is sensed to be free, the Bcounter is decremented by 1 until it reaches 0. Then, transmission starts.

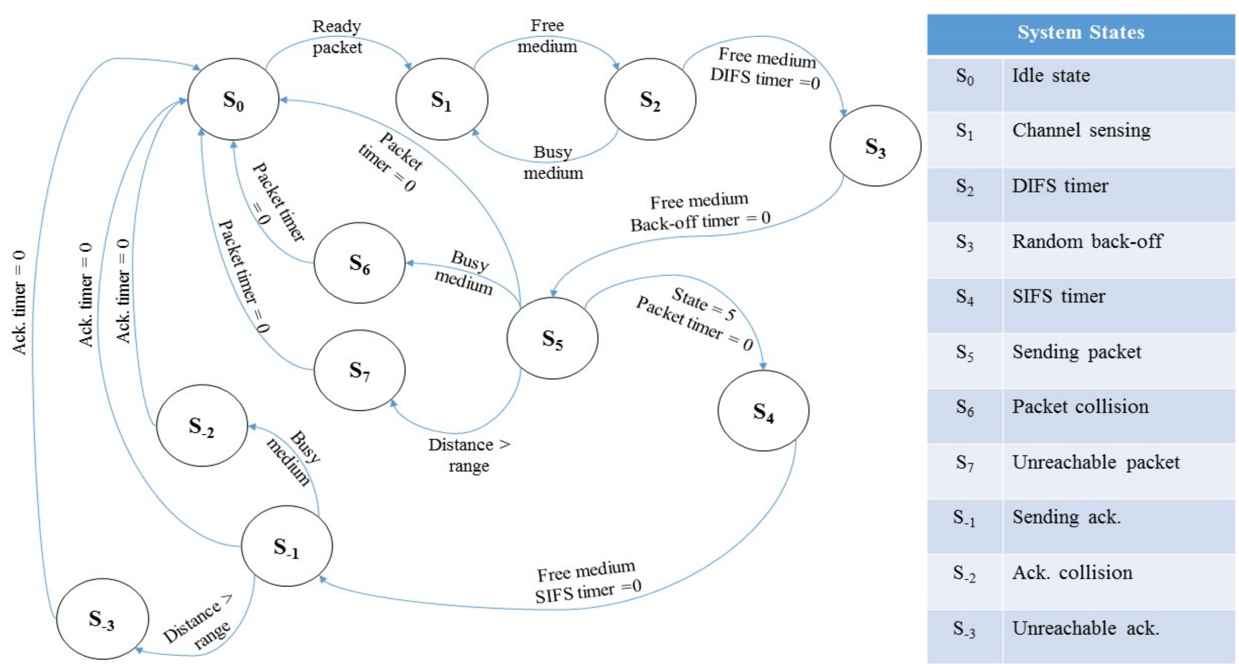


Fig. 4 Proposed CSMA/CA State diagram

If however the channel is sensed to be busy, the Bcounter is frozen and the process is only then resumed when the channel is idle again [12].

In ***Fig. 4*** the proposed state diagram for modeling CSMA/CA algorithm is also divided into 3 main stages; stage 1 is where the channel is sensed. Stage 2 denotes the packet transmission. Stage 3 represents the acknowledgment transmission [14].

A. Stage 1: CSMA/CA Channel Sensing

In state S_0, the node checks whether there is a packet ready to be sent. If true, the node proceeds to state S_1 where the channel is primarily sensed. If idle, the node proceeds to state S_2. The channel is sensed for the DIFS period. If the channel is busy at any time during the DIFS, the node returns back to state S_1. If the channel is idle during the whole DIFS time, it proceeds to state S_3. At state S_3, a timer is set with the value of the random back-off and the channel is sensed. Whenever the channel is free, the timer is decremented. Whenever the channel is busy, the timer is frozen. When the random back-off timer reaches a value of 0, state S_5 is proceeded to which denotes the start of stage 2.

B. Stage 2: CSMA/CA Packet Sending

In state S_5, the node sets a timer with the value of the packet length. The channel is sensed. If busy, state S_6 is proceeded to where the packet is reported to be collided. If the distance between the node and its destination is greater than the range of the node, the packet is considered unreachable and state S_7 is reached. If during the whole time the channel is free and the distance is smaller than the range, state S_4 is proceeded to denoting that the packet is successfully sent.

C. Stage 3: CSMA/CA Acknowledgment Sending

In state S_4, the receiver of the packet sets the Short inter frame space (SIFS) timer to sense the channel during that time to get ready to send the acknowledgment to the sender. If the channel is free, the timer is decremented. Otherwise, the timer is frozen. When the timer reaches a value of 0, the receiver starts sending the acknowledgment to the original node and state S_{-1} is reached. The channel is sensed. If busy, state S_{-2} is proceeded to and a packet collision is reported. The distance is then measured. If found to be greater than the range, the acknowledgment is considered unreachable and state S_{-3} is reached. If the channel is free and the distance is smaller than the range for the whole acknowledgment length, the acknowledgment is successful.

IV. SIMULATION RESULTS

Using excessive Matlab-based simulations, the performance of both LBE-based LBT and CSMA/CA is observed, assuming that all the nodes are within the range of each other and are stationary; hence the performance is affected only by collision. The performance during high competition between the nodes to access the channel is measured by how often collisions happen.

The traffic justifies the probability of having a packet ready to be transferred and it is checked at the beginning of each cycle.

In this simulation two values for traffic are considered: 1 denoting saturated situation and 0.5 indicating half load situation. The variable q can take any value between 4 and 32. However the simulation takes deterministic values namely 4, 8, 16 and 32. The efficiency is calculated using equation 2.

$$Efficiency = \frac{Successfully\ transmitted\ packets}{Total\ number\ of\ packets} \qquad (2)$$

A. LBE-based LBT

Fig. 5 illustrates the relation between the efficiency and the number of nodes with altering q-values and fixed traffic value of 1 to show the effect of high competition on the performance of the transmission.

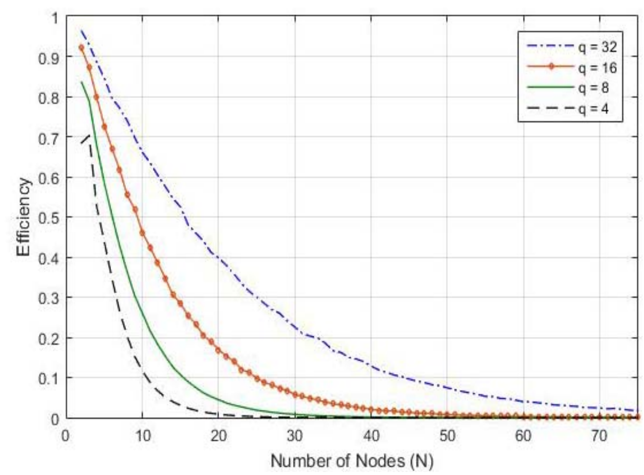


Fig. 5 Efficiency for LBE-based LBT with different q values

It is clear that the efficiency decreases exponentially with the increase in number of nodes for all q-values. At any fixed number of nodes, the higher the value of q the better the efficiency. At a node number of 10, the efficiency for a q-value of 4 barely reaches 10%. It increases with an increasing q-value to about 25%, 45% and 77% for q=8, 16 and 32 respectively. However, as the number of nodes reaches 70, the difference in efficiency decreases and the efficiency tends to zero for all q-values.

This can interpreted as follows: With a higher number of nodes, the efficiency decreases as the competition between the nodes increases, increasing thereby the collision rate. Since N is a random number ranging from 1 to q, an increase in q leads to an increase in the value N can take. The CW is directly proportional to N and its maximum value therefore increases too. This leads to the reduction of the competition between the nodes. Hence, the collision between the packets is less, and efficiency increases with the increase of q.

Table 1 illustrates the relation between the efficiency and the number of nodes using two different values for traffic and random number for q which is uniformly distributed from 4 to 32.

N	2	5	10	20	40	60
Efficiency at traffic =1	0.89	0.72	0.47	0.18	0.027	0
Efficiency at traffic = 0.5	0.93	0.75	0.50	0.20	0.028	0

Table 1 Comparison between the efficiency for LBE-based LBT nodes at different traffic values

The efficiency is significantly higher for a lower number of users N. When the traffic decreases from 1 to 0.5, the efficiency experiences a slight increase. However, the difference in efficiency for different traffic values decreases with the increase in number of nodes. For instance, there is a difference of 4% between the two traffic values for 2 nodes. For 10 nodes, the difference between the efficiencies decreases to reach 3%. At 20 nodes, it becomes 2% and tends to zero for a number of nodes higher than 50.

If the traffic has a value of 0.5, this indicates that at the first cycle half the number of nodes have a packet ready to be sent. The efficiency is not dramatically affected as the accumulation of the nodes to sense the channel does not decrease significantly. This is because the traffic that indicates the probability of sending for every node is checked every cycle. A large number of nodes from the previous cycles will still be checking the channel.

B. CSMA/CA

To compare between the performance of LTE and Wi-Fi, a unified packet length is set. In the case of CSMA/CA, q symbolizes only the packet length which is equal to the CoT. To calculate CoT, q takes the same values as mentioned above. The relation between the efficiency and the number of nodes using the different values of q and fixed traffic equal to 1 is demonstrated in the figure below.

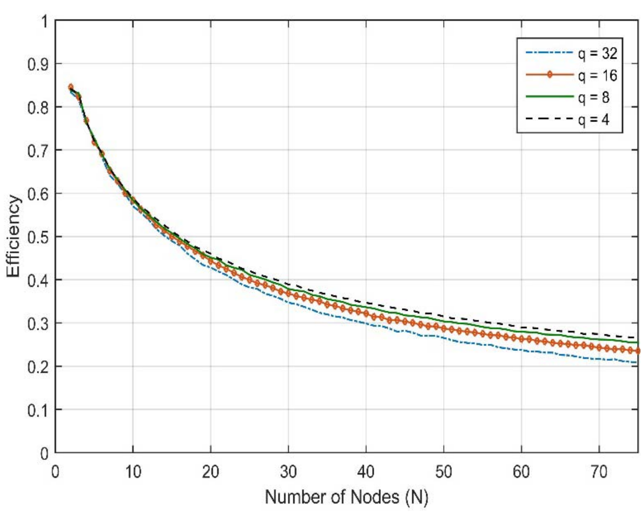


Fig. 6 Efficiency for CSMA/CA with different q values

Again, the efficiency decreases with the increase in number of nodes for all q-values. For a fixed number of nodes, the efficiency is slightly less for a higher q-value. For 10 nodes, the difference of efficiencies between the 4 q-values is hardly recognizable. However, for 70 nodes the graph of q= 32 shows the least efficiency of around 20% whereas the graphs of q= 16, 8 and 4 show an increased efficiency of about 22, 25 and 26% respectively.

When the number of nodes is high, the probability for a collision is higher as in LBE-based LBT. Therefore, the efficiency is low. The value of q represents only the length of the packet and does not affect the CW in CSMA/CA which causes only a slight change in the efficiency. Therefore, when a node occupies a channel during a longer time (higher q value), the probability for a collision becomes higher. Hence, the efficiency of the longest packet is the least.

Table 2 shows the behavior of CSMA/CA similar to the behavior of LBE-based LBT discussed above (***Table 1***) with different values. The values of q are random numbers uniformly distributed from 4 to 32 for CSMA/CA.

N	2	5	10	20	40	60
Efficiency at traffic =1	0.84	0.72	0.57	0.43	0.31	0.25
Efficiency at traffic = 0.5	0.88	0.75	0.6	0.45	0.32	0.25

Table 2 Comparison between the efficiency for CSMA/CA nodes at different traffic values

Again, the difference between the efficiencies for different traffics decreases with the increasing number of nodes. The accumulation of nodes similar to the discussed one in table 1 takes place resulting in the slight increase in the efficiency when the traffic is decreased from 1 to 0.5.

C. Comparison between LBE-based LBT and CSMA/CA

A comparison between ***Fig. 5*** and ***Fig. 6 Efficiency for CSMA/CA with different q values*** is shown below in ***Fig. 7*** to demonstrate the difference between the efficiencies of both systems.

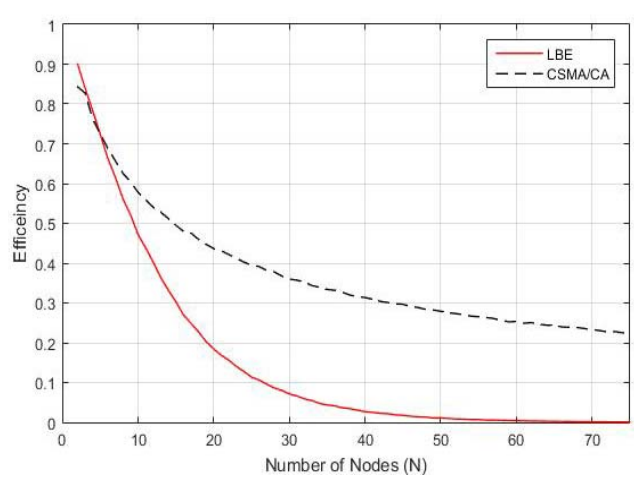


Fig. 7 Efficiency for LBE-based LBT and CSMA/CA with average q value

The figure illustrates a general decrease in efficiency with an increase in number of nodes for both LBE-based LBT and

CSMA/CA, taking in consideration that traffic is taken equal to 1 and q is a random variable as mentioned above.

For a number of nodes less than 10, both systems are almost equal in efficiency. For 10 nodes, they begin to deviate; LBE-based LBT has an efficiency of almost 50% while CSMA/CA shows an efficiency of 60%. However, at a higher number of nodes, the efficiencies diverge from each other, showing a higher efficiency for CSMA/CA than LBE-based LBT. The difference between both efficiencies reaches about 22% for 70 nodes. That is due to the exponential CW of CSMA/CA.

V. Conclusion

The study conducted analyzes the performance evaluation of LBE-based LTE and compares it with the performance of CSMA/CA under similar conditions. The CSMA/CA model is set as a benchmark for assessing the performance of LBE-based LTE. Two methods for modelling the two MAC systems are proposed and implemented using Matlab. Under the assumption that the performance is only affected by collision, it is found that the efficiency of both LBE-based LBT and CSMA/CA is significantly lower for a large number of nodes. However, when compared to one another, CSMA/CA performance is much better than LBE when exposed to high number of nodes, but at low competition LBE shows acceptable efficiency compared to CSMA/CA. Reducing the q values leads to the deterioration of LBE-based LBT performance and an enhancement in the Wi-Fi efficiency.

A near-future research about the co-existence and mutual benefit of MAC of Wi-Fi and LAA LTE is to be conducted, aiming at providing advantage and profit to both systems while working together. The target is to find some kind of interaction between the two systems aiming to use any advantage in one system and apply it to the other so that the whole spectrum utilization is improved.

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