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Research Article

Cross Layer Optimization and Simulation of Smart Grid Home Area Network

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An electrical "Grid" is a network that carries electricity from power plants to customer premises. Smart Grid is an assimilation of electrical and communication infrastructure. Smart Grid is characterized by bidirectional flow of electricity and information. Smart Grid is a complex network with hierarchical architecture. Realization of complete Smart Grid architecture necessitates diverse set of communication standards and protocols. Communication network protocols are engineered and established on the basis of layered approach. Each layer is designed to produce an explicit functionality in association with other layers. Layered approach can be modified with cross layer approach for performance enhancement. Complex and heterogeneous architecture of Smart Grid demands a deviation from primitive approach and reworking of an innovative approach. This paper describes a joint or cross layer optimization of Smart Grid home/building area network based on IEEE 802.11 standard using RIVERBED OPNET network design and simulation tool. The network performance can be improved by selecting various parameters pertaining to different layers. Simulation results are obtained for various parameters such as WLAN throughput, delay, media access delay, and retransmission attempts. The graphical results show that various parameters have divergent effects on network performance. For example, frame aggregation decreases overall delay but the network throughput is also reduced. To prevail over this effect, frame aggregation is used in combination with RTS and fragmentation mechanisms. The results show that this combination notably improves network performance. Higher value of buffer size considerably increases throughput but the delay is also greater and thus the choice of optimum value of buffer size is inevitable for network performance optimization. Parameter optimization significantly enhances the performance of a designed network. This paper is expected to serve as a comprehensive analysis and performance enhancement of communication standard suitable for Smart Grid HAN applications.

1. Introduction

The power grid around the world is going through a substantial and drastic transformation through Smart Grid technology. Smart Grid is the most ingenious and imaginative technology of existent era. An existing power grid lacks reliability, remote monitoring and control, automation, sensing, disaster recovery, security, and efficiency [1]. Smart Grid technology is an integration of electrical and communication infrastructure with bidirectional flow of electricity and information. It ensures reliable power distribution through real time monitoring and control of generation, transmission, and distribution parameters. Sensing, communication, and automation are the core constituents of Smart Grid infrastructure [2]. Internet has paved the way for Smart Grid design and deployment. Smart Grid includes hierarchical and heterogeneous layers as well as standards. Smart Grid comprises three main hierarchical layers such as Home Area Network (HAN), Neighbourhood Area Network (NAN), and Wide Area network (WAN). Home Area Network is meant for consumer premises. It comprises Wireless Sensor Network (WSN), home appliances, smart meters, renewable energy resources, Plug-in Hybrid Electric Vehicles (PHEVs), and so on for its operation [3].

Various standards such as IEEE 802.11, IEEE 802.15.1, IEEE 802.15.4, and IEEE 802.16 can be used for HAN [4–8]. NAN is a combination of HANs and appropriate for distribution automation. WAN shelters HAN and NAN for

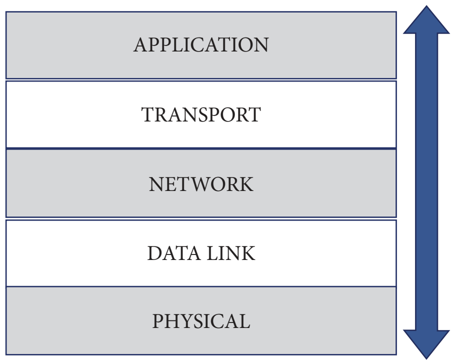

Figure 1: Conceptual diagram of cross layer optimization.

monitoring and control of complete communication network [9]. WAN is a huge network covering management of generation, transmission, distribution, and utilization of entire grid.

Thus, Smart Grid is characterized by combination of various communication standards and complex infrastructure [10–12]. The complexity of Smart Grid necessitates a novel approach for network optimization.

Communication protocols are designed using layered approach in which each layer is meant to perform a specific function in alliance with the rest of the layers. In layered approach, different layers function autonomously. A particular layer is concerned about a layer located above or below it only for the sake of some degree of responses and exchanges. A layered approach can be amended with cross layer approach [13]. Cross layer optimization explores synergy between different layers for the improvement of network performance. It is a joint optimization of different layers which explores dependence between layers. Figure 1 shows the conceptual diagram of cross layer design.

Cross layer optimization can be realized for performance improvement either through joint optimization of parameters concerning various network layers or by exchange of information between different network layers. Parameter optimization of one layer must result in overall network performance improvement [14].

2. Cross Layer Parameter Optimization of Home/Building Area Network

This section illustrates the parameter optimization of a Smart Grid building/Home Area Network designed using IEEE 802.11n standard. Various scenarios are executed and investigated for performance optimization in RIVERBED OPNET modeler. IEEE 802.11 is chosen for HAN as it satisfies the QoS requirements for home automation [15].

IEEE 802.11a, IEEE 802.11b IEEE 802.11g, and IEEE 802.11n are the various versions of WLAN standard. IEEE 802.11n standard is implemented with block acknowledgement and frame aggregation parameters for reduction in MAC overhead. IEEE 802.11n standard with 5 GHz bandwidth and 65 Mbps base data rate is chosen for network optimization.

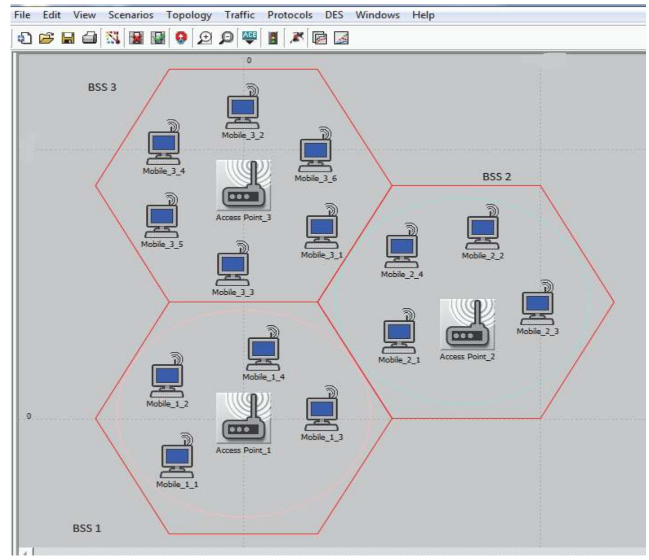

Figure 2: Diagram of the network to be optimized.

Joint parameter optimization of PHY and MAC layer is performed for performance enhancement. The simulations are performed for default parameters as well as optimized parameters.

Figure 2 shows the network designed for optimization using simulation based approach.

2.1. WLAN Configuration. Figure 2 shows the three Wireless Local Area Network (WLAN) infrastructure networks. Three access points are considered with different features for comparative analysis of different parameters [16, 17]. In access point 1, block acknowledgement is disabled and in two other access points, the same is enabled. There are different versions of IEEE 802.11 standard. IEEE 802.11n protocol is used.

The basic IEEE 802.11 standard provides the data throughput of 2 Mbps. IEEE 802.11b standard provides maximum data throughput of 11 Mbps. IEEE 802.11a and IEEE 802.11g provide maximum data rates of 54 Mbps. IEEE 802.11n is an upgraded protocol in terms of PHY and MAC enhancements. Basic Service Set (BSS) 1 with access point 1 operates in IEEE 802.11n 20 MHz band with block acknowledgement inactivated. BSS 2 with access point 2 operates in IEEE 802.11n 20 MHz band with block acknowledgement enabled. BSS 3 with access point 3 operates in IEEE 802.11n 40 MHz band with block acknowledgement enabled. A short guard band is enabled for all three configurations. The data throughput of 65 Mbps base and 600 Mbps maximum is selected for OPNET simulation. The theoretical value of maximum data throughput for IEEE 802.11n standard is 600 Mbps [17].

2.2. Effect of Block Acknowledgement Mechanism. Block acknowledgement method decreases overhead as the data frame is acknowledged in a sole frame. Throughput indicates the overall number of bits per second forwarded from lower layer to upper layers.

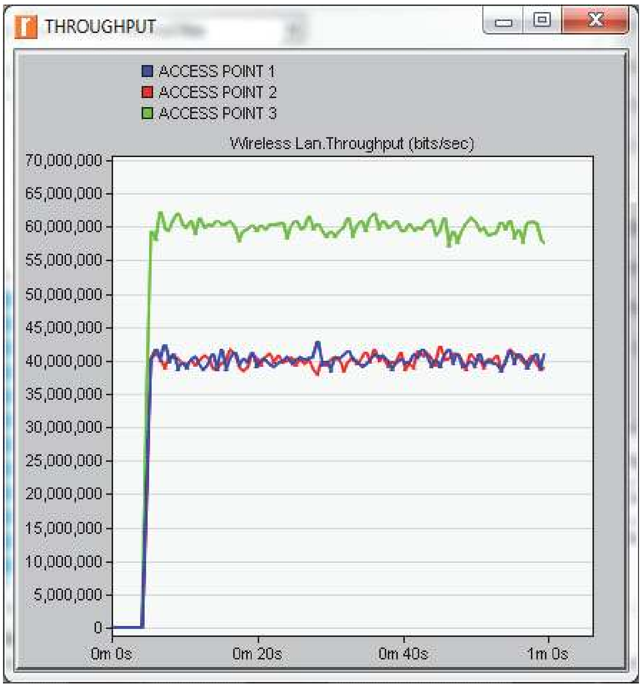

Figure 3: WLAN throughput of different access points.

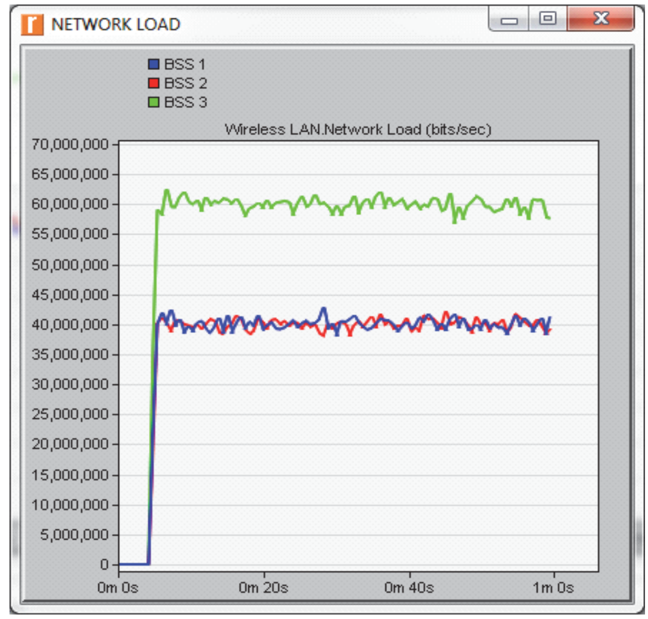

Figure 4: Network load of different BSSs.

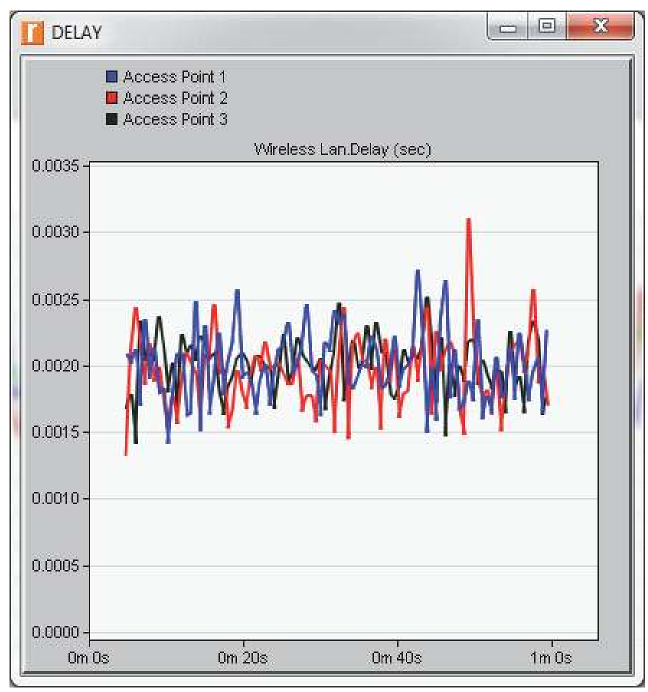

Figure 5: Wireless LAN delay of different WLAN access points.

Media access delay includes contention delay, queuing delay, and block acknowledgement request frames by all WLAN MACs. It also includes successful RTS-CTS exchanges during frame transmission. Delay includes end to end delay of all packets received by MAC layer of all nodes and sent to upper layers. If access point functionality is enabled, then this delay also includes MAC delay of resource MAC, separate reception of all fragments, and transfer of frame through an access point.

Results depict that the data throughput is maximum for BSS 3 with access point 3. The throughput is minimum for BSS 1 with access point 1. It is evident from the results that the use of block acknowledgement function increases the throughput as the data frame is acknowledged in a sole block which significantly reduces overhead. Moreover, the performance of RTS mechanism and block acknowledgement is compared which shows that the delay for RTS is higher with threshold value of 256. The above network configuration can be used for home or building area network and it can also be expanded for NAN. Graphical results are illustrated below. Figure 3 shows the simulation results of WLAN throughput of different access points.

Figure 4 shows the network load of all three BSSs. The network load is maximum for BSS 3 with block acknowledgement enabled. Figures 5 and 6 show the WLAN delay and media access delay, respectively, for different access points.

It is evident from the simulation results that the lowest media access delay is obtained for access point 3 as an overhead is significantly reduced.

As shown in Figure 7, block acknowledgement mechanism is compared with RTS with the threshold value of 256. WLAN throughput is maximum in case of block acknowledgement mechanism.

Media access delay and WLAN delay are drastically reduced by enabling block acknowledgement mechanism as shown in Figures 8 and 9, respectively.

2.3. Effect of Fragmentation Threshold. Fragmentation threshold states the fragmentation threshold in bytes as well

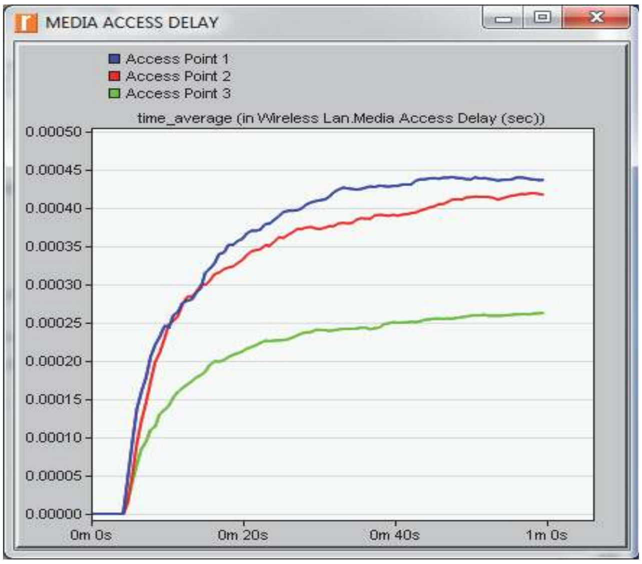

FIGURE 6: WLAN media access delay of different access points.

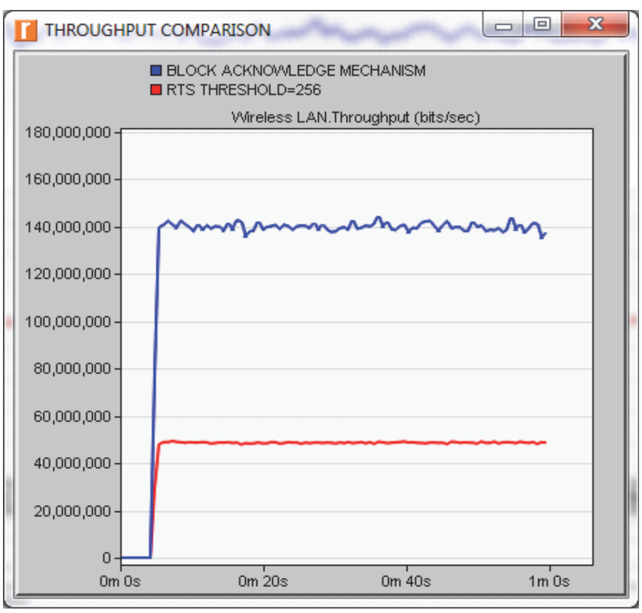

FIGURE 7: WLAN throughput comparison for block acknowledgement versus RTS mechanism.

as the size of the fragments except for the last fragment. Any data packet received from higher layer with a size larger than this threshold will be divided into fragments, which will be transmitted separately over the radio interface.

Since this threshold also determines the size of the largest allowed fragment, depending on its value and the sizes of received data packets, some packets can be divided into more than two fragments. Special value "None" shows that fragmentation will not be used for the transmission of any higher layer data packet regardless of its size. Results demonstrate that the fragmentation increases total delay and

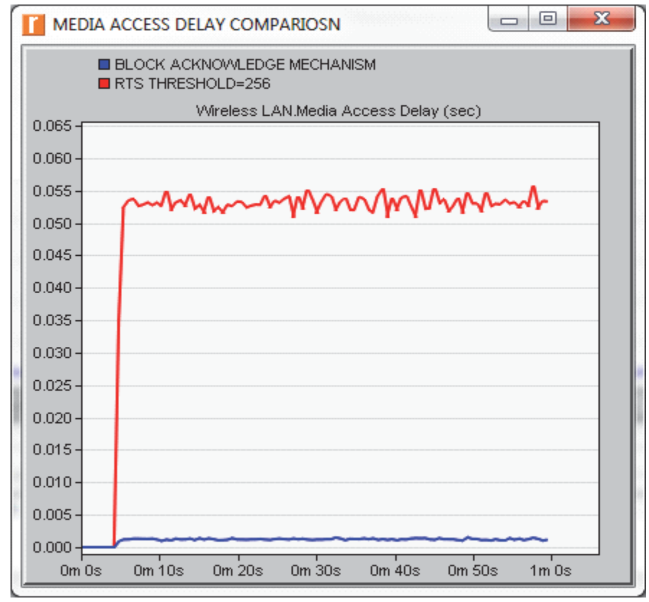

FIGURE 8: WLAN media access delay comparison for block acknowledgement versus RTS mechanism.

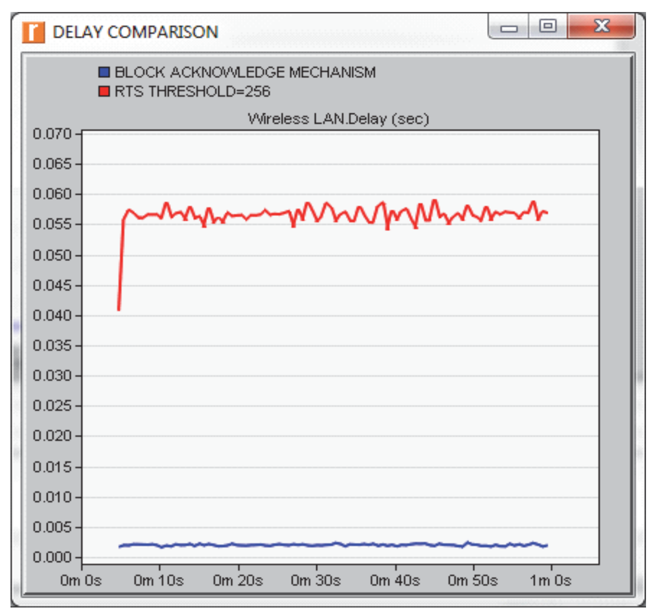

FIGURE 9: WLAN delay comparison for block acknowledgement versus RTS mechanism.

media access delay as shown in Figures 10 and 11, respectively. Fragmentation reduces retransmission attempts as shown in Figure 12. Throughput is also reduced as an effect of fragmentation process as shown in Figure 13.

Higher value of fragmentation threshold reduces WLAN and media access delays as shown in Figures 14 and 15, respectively. Retransmission attempts are reduced due to fragmentation as shown in Figure 16.

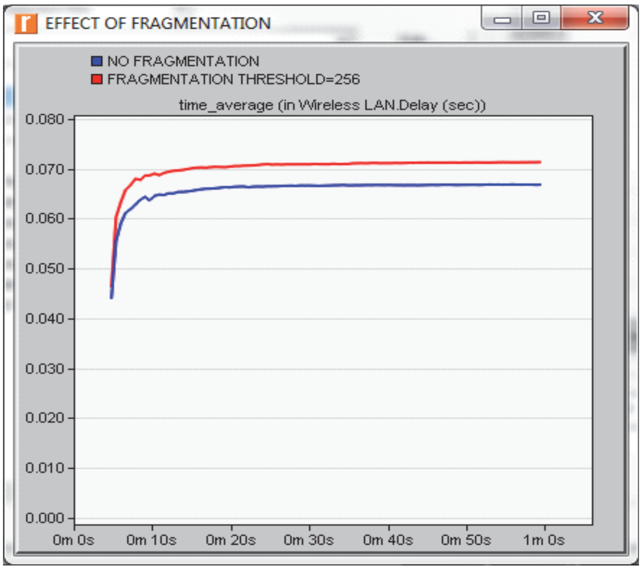

Figure 10: Wireless LAN delay with and without fragmentation.

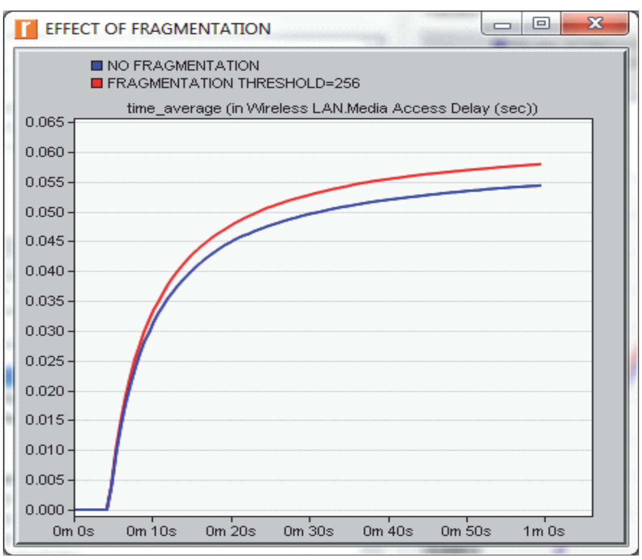

Figure 11: WLAN media access delay with and without fragmentation.

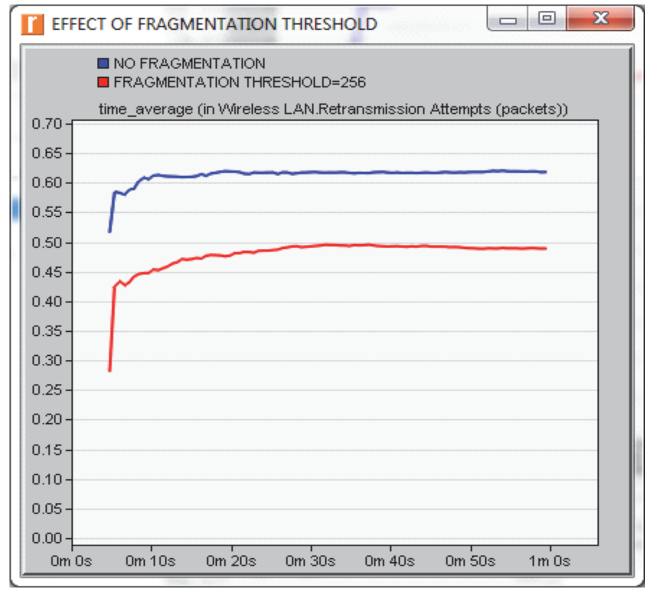

Figure 12: WLAN retransmission attempts with and without fragmentation.

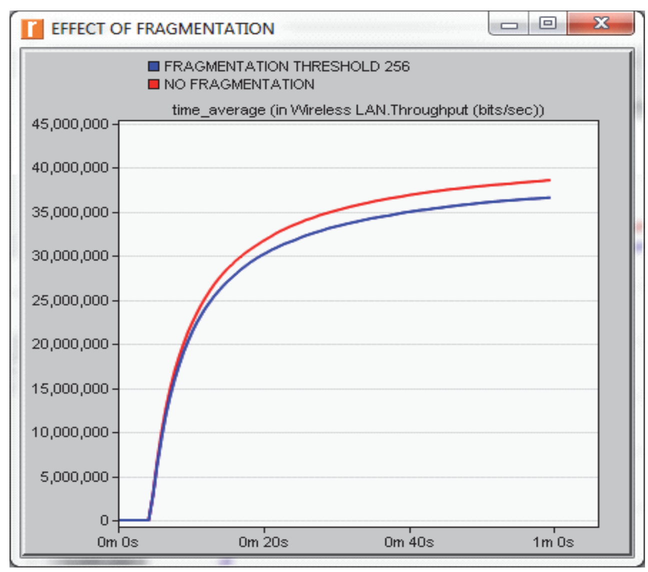

Figure 13: WLAN throughput with and without fragmentation.

Figure 17 shows the throughput obtained without fragmentation and with different values of fragmentation thresholds. Simulation results show that the throughput is minimum for lower values of fragmentation threshold. Results show that the WLAN and media access delays are reduced by combination of fragmentation and RTS mechanism as shown in Figures 18 and 19, respectively. Retransmission attempts are also reduced with fragmentation as shown in Figure 20. This combination significantly improves network throughput as shown in Figure 21.

As shown in Figures 18 and 19, the optimum results are obtained when the value of RTS and fragmentation threshold is 1024. Combination of optimal values of these parameters significantly reduces overall as well as MAC delay.

Simulation results are obtained for different values of RTS and fragmentation thresholds as shown in Figure 22. It is apparent from the graphical results that higher values of RTS and fragmentation thresholds result in higher network throughput.

Figure 23 shows that there is a significant reduction in overall delay as well as media access delay when frame aggregation mechanism is combined with RTS.

Figure 24 shows the simulation results obtained for different values of RTS and fragmentation thresholds. It is apparent from simulation results that media access delay decreases with higher values of RTS and fragmentation thresholds.

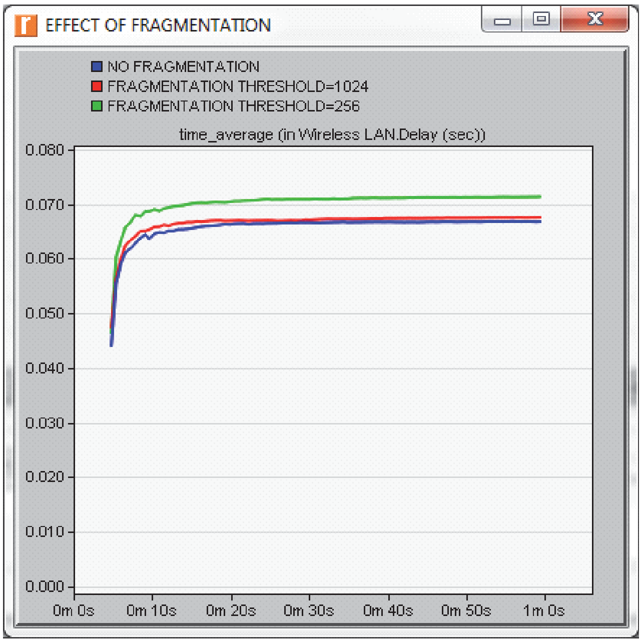

Figure 14: WLAN delay with different fragmentation thresholds and without fragmentation.

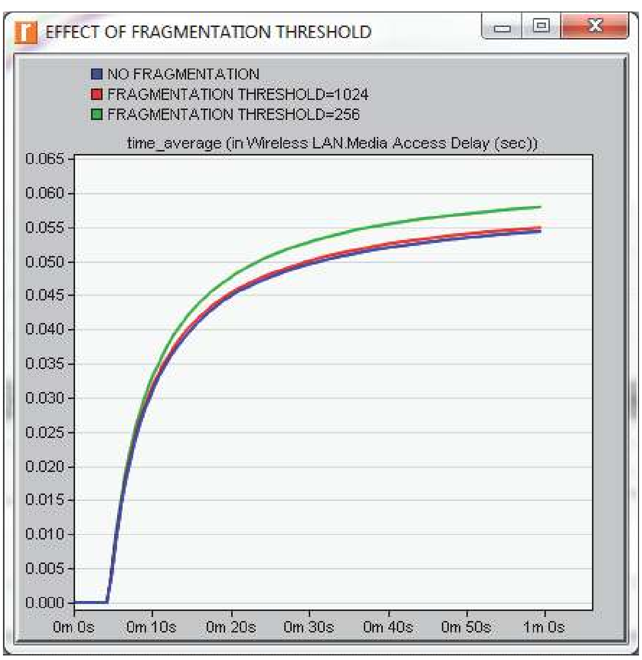

Figure 15: WLAN media access delay with different fragmentation thresholds and without fragmentation.

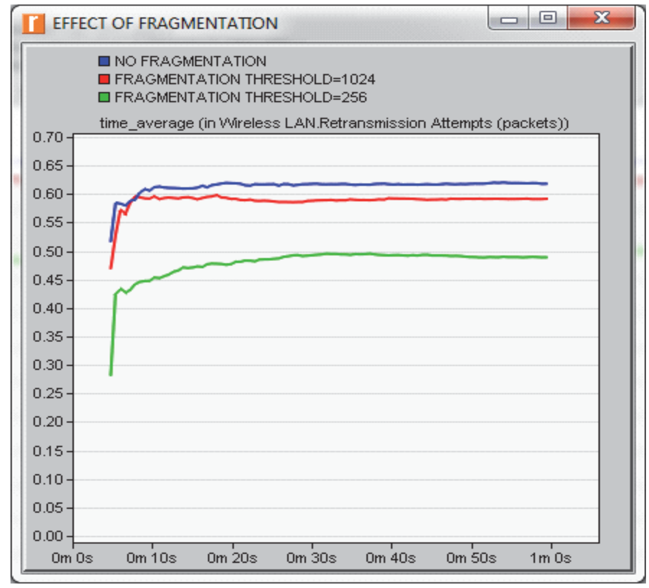

Figure 16: WLAN retransmission attempts with different fragmentation thresholds and without fragmentation.

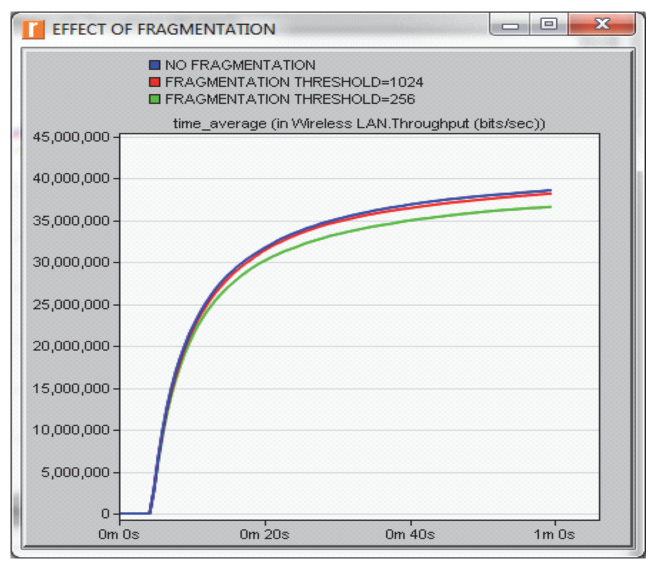

Figure 17: WLAN throughput with different fragmentation thresholds and without fragmentation.

2.4. Effect of Buffer Size. Buffer size states the maximum size of the higher layer data buffer in bits. Once the buffer limit is reached, the data packets that arrived from upper layer will be removed until some packets are discarded from the buffer so that the buffer has some unoccupied space to assemble these new packets. Increased buffer size increases the throughput but also increases the delay as shown in Figures 25 and 26, respectively. Media access delay also increases for higher values of buffer size as shown in Figure 27. Thus an optimal value of buffer size should be selected to enhance the network performance.

2.5. Effect of Greenfield Operation. This feature enables or disables Greenfield operation in a high throughput station. If the Greenfield operation is aided, then the high throughput station can use High Throughput-Greenfield Physical Layer Convergence Procedure (PLCP) header for data frames when communicating with another Greenfield capable high throughput station.

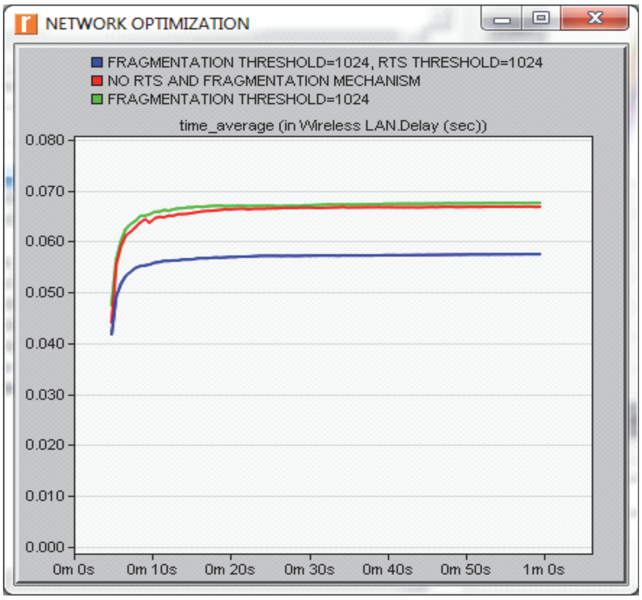

Figure 18: WLAN optimization with RTS and fragmentation mechanisms.

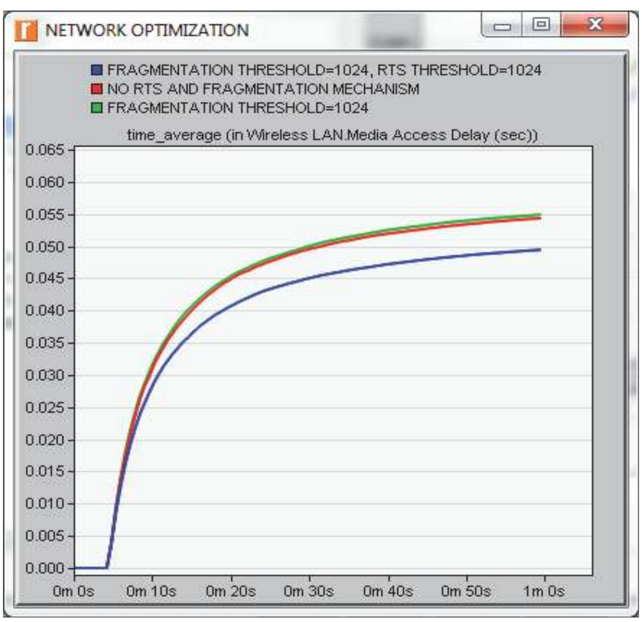

Figure 19: WLAN delay optimization with RTS and fragmentation mechanism.

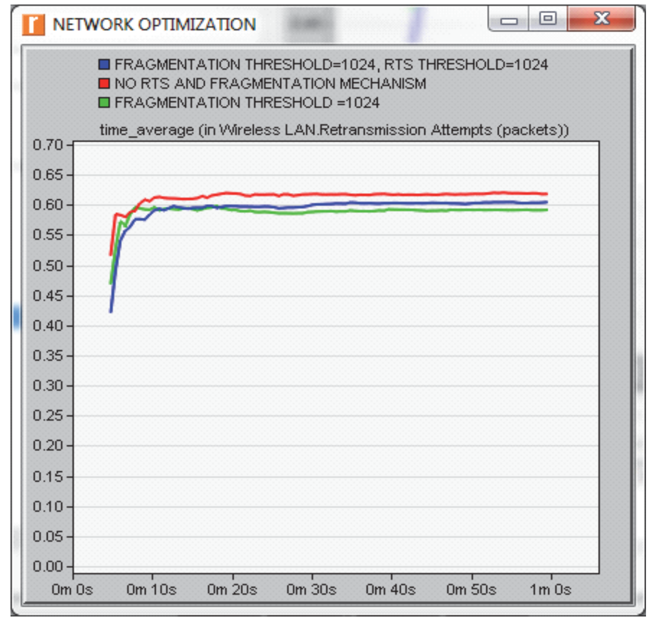

Figure 20: WLAN retransmission attempts optimization with RTS and fragmentation mechanisms.

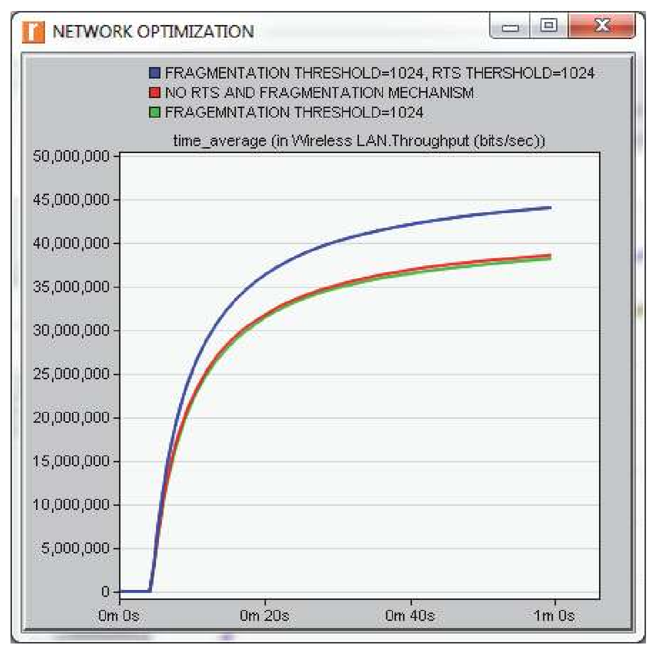

Figure 21: WLAN throughput optimization with RTS and fragmentation mechanisms.

It is observed from the simulation results shown in Figure 28 that the throughput increases when Greenfield operation is enabled. Greenfield operation combined with RTS and fragmentation mechanism further increases throughput and lessens delay. As shown in Figure 29, Greenfield operation is linked with higher values of RTS and fragmentation thresholds for throughput improvement.

The combination of various parameters such as Greenfield, RTS, and fragmentation reduces WLAN delay as well as media access delay as shown in Figures 30 and 31, respectively.

2.6. Effect of Contention Window Optimization. Contention is a media access methodology used for sharing a medium. CWmin specifies the starting size of the Contention Window for the Best Effort access category, which is used to pick the random number of slots for the back-off periods.

CWmax states the maximum size of the Contention Window for the Best Effort access category, which is used to select the random number of slots for the back-off periods.

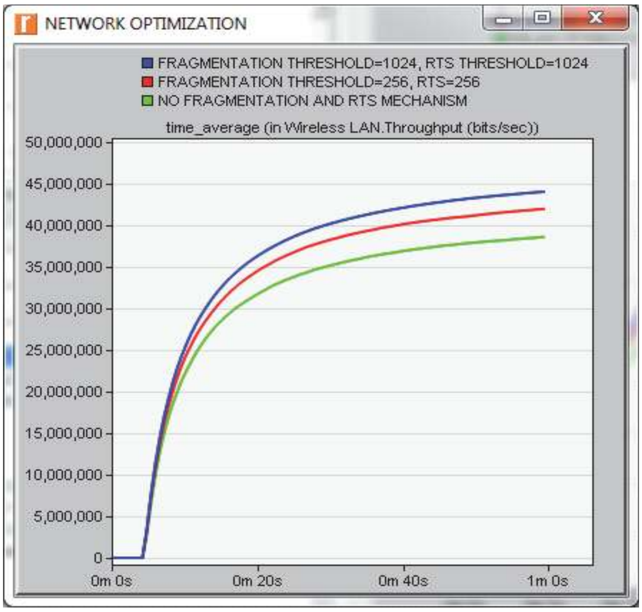

Figure 22: WLAN throughput optimization with different values of RTS and fragmentation thresholds.

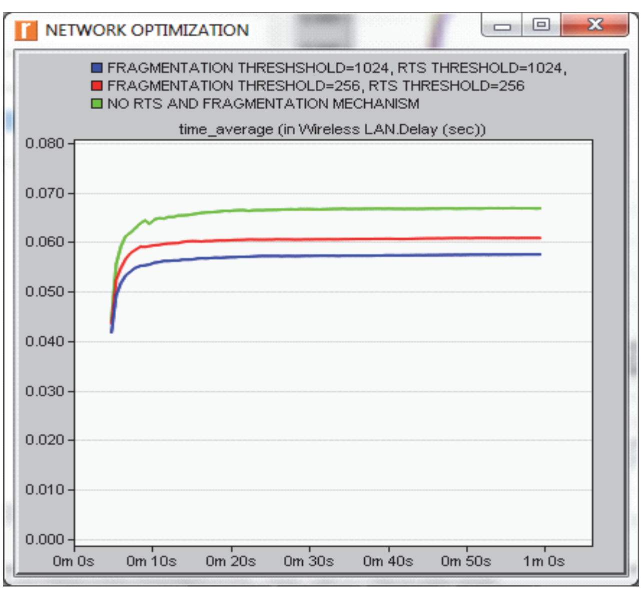

Figure 23: WLAN delay optimization with different values of RTS and fragmentation thresholds.

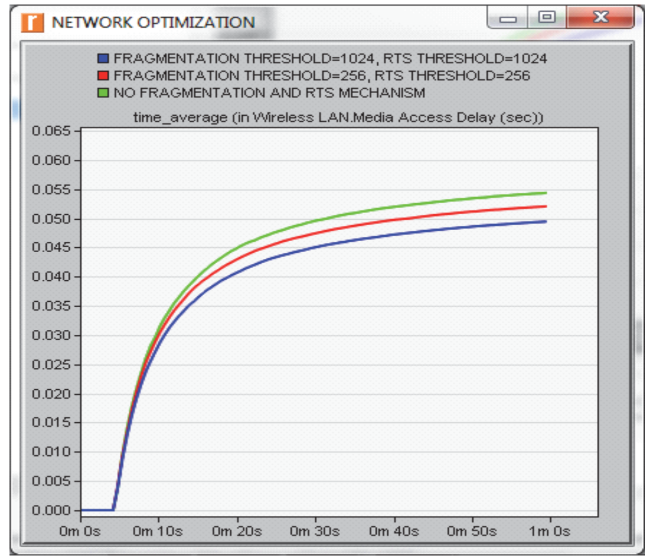

Figure 24: WLAN media access delay optimization with different values of RTS and fragmentation thresholds.

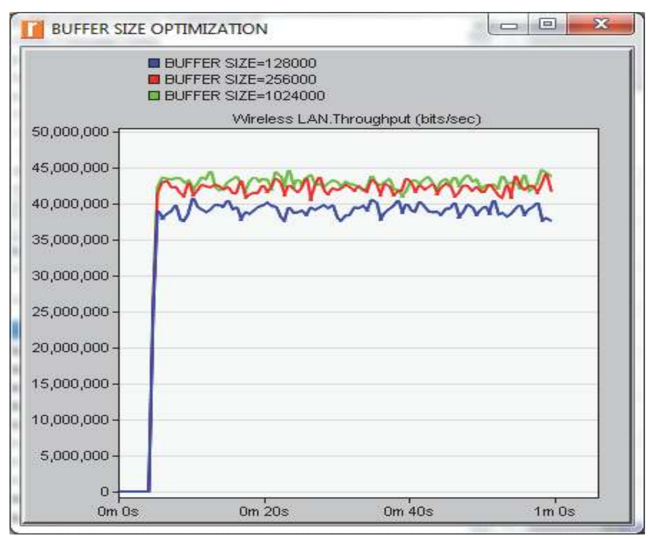

Figure 25: WLAN buffer size optimization for higher throughput.

Figures 32 and 33 show the default and optimized values, respectively, for CWmin and CWmax. Results are drawn for default values of CWmin and CWmax which are (−1) for IEEE 802.11e standard. Results are upgraded for optimized value of CWmin and CWmax.

As shown in Figure 34, WLAN delay is reduced for optimized values of CWmin and CWmax. Media access delay is also reduced for optimized values of CWmin and CWmax as shown in Figure 35.

2.7. Effect of Frame Aggregation. Frame aggregation is a technique to send two or more frames in a single transmission to increase the throughput. As the data rates increase, overhead also increases which consumes very high bandwidth. This issue can be proficiently addressed by using frame aggregation method. Frame aggregation is categorized into two methods, namely, MAC Service Data Unit (MSDU) and MAC Protocol Data Unit (MPDU) aggregation. MSDU allows multiple MAC Service Data Units to the same receiver contained in single MPDU. MPDU combines multiple subframes into single header. Figure 36 shows the values of various frame aggregation parameters considered for simulation. Frame aggregation reduces delay but the throughput is also reduced as shown in the graphical representations.

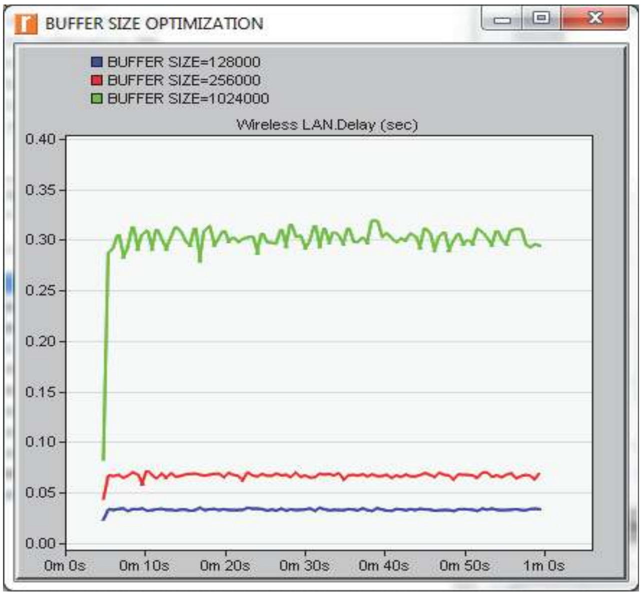

Figure 26: WLAN buffer size optimization for lower delay.

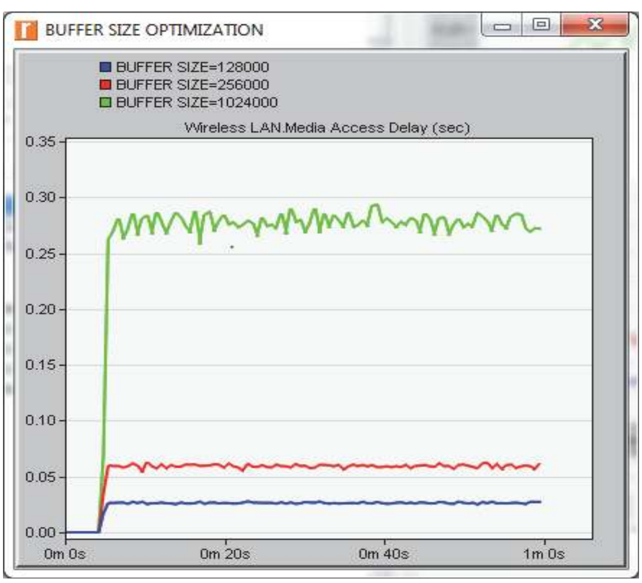

Figure 27: WLAN buffer size optimization for lower media access delay.

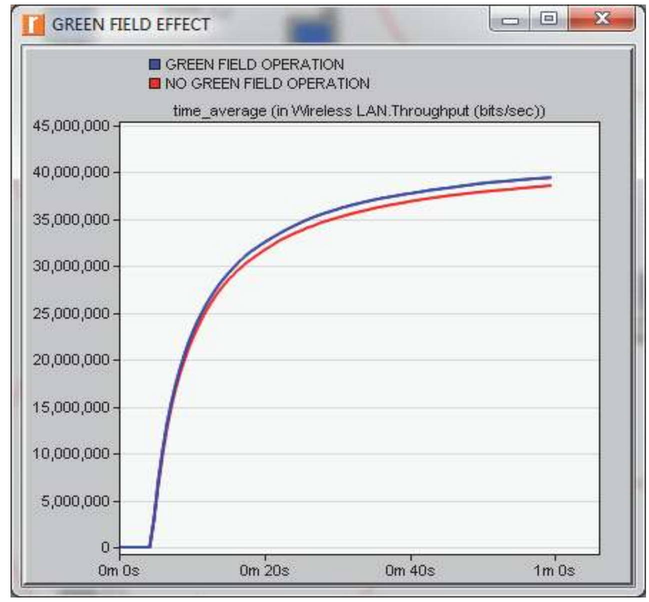

Figure 28: WLAN throughput optimization with Greenfield operation.

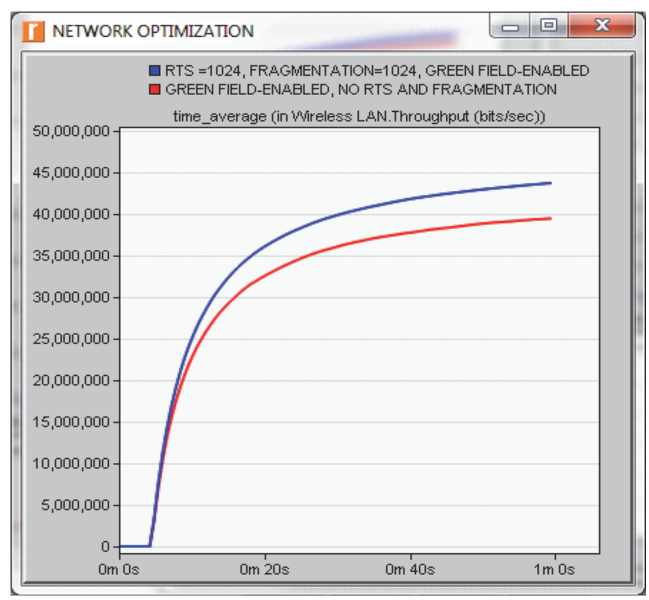

Figure 29: WLAN throughput optimization with RTS, fragmentation, and Greenfield operation parameters.

Simulation results shown in Figures 37 and 38 illustrate that media access delay as well as throughput decreases when frame aggregation is enabled.

To overcome this performance degradation, frame aggregation method is used along with RTS and fragmentation mechanism. For optimization, higher values of RTS and fragmentation threshold (1024) are selected.

As a result of this combination, delay is reduced and throughput is considerably improved as shown in Figures 39 and 40, respectively. Media access delay is also significantly reduced as shown in Figure 41.

Figure 42 shows the various parameters considered for performance optimization. Simulation results shown in Figure 43 show the throughput for distinct as well as combined parameter optimization.

3. Results and Discussions

This paper explores parameter optimization of Home Area Network based on IEEE 802.11n standard. The HAN is designed, optimized, and simulated using OPNET modeler.

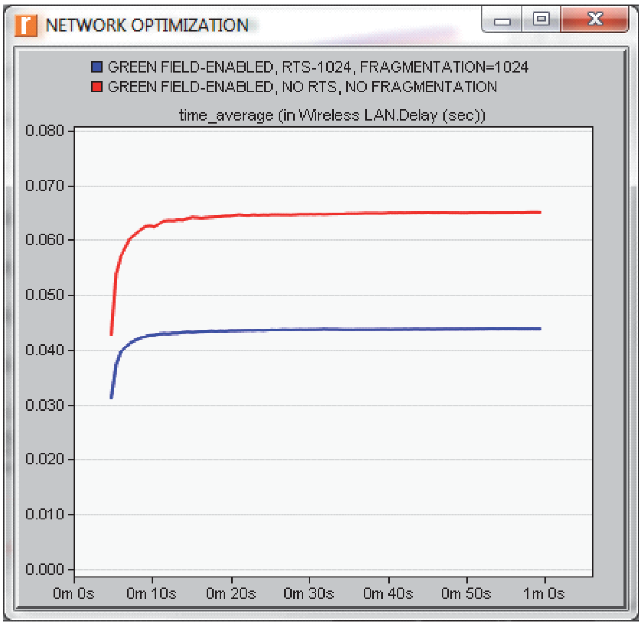

Figure 30: WLAN throughput optimization with RTS, fragmentation, and Greenfield operation parameters.

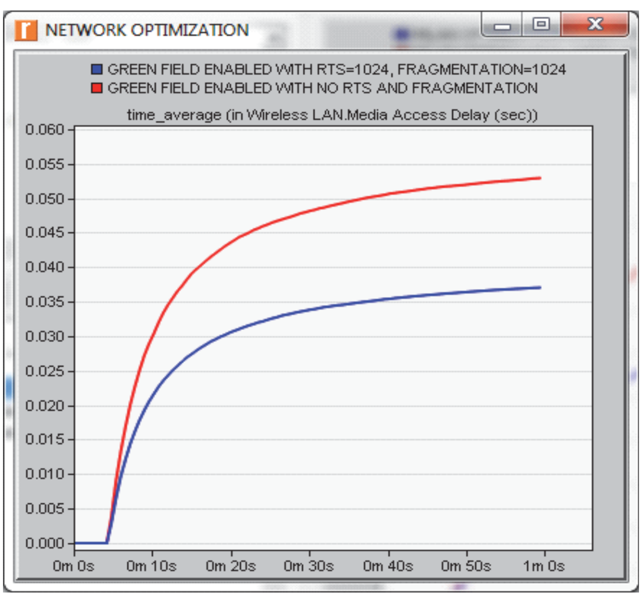

Figure 31: WLAN media access delay for optimized value of RTS, fragmentation, and Greenfield operation parameters.

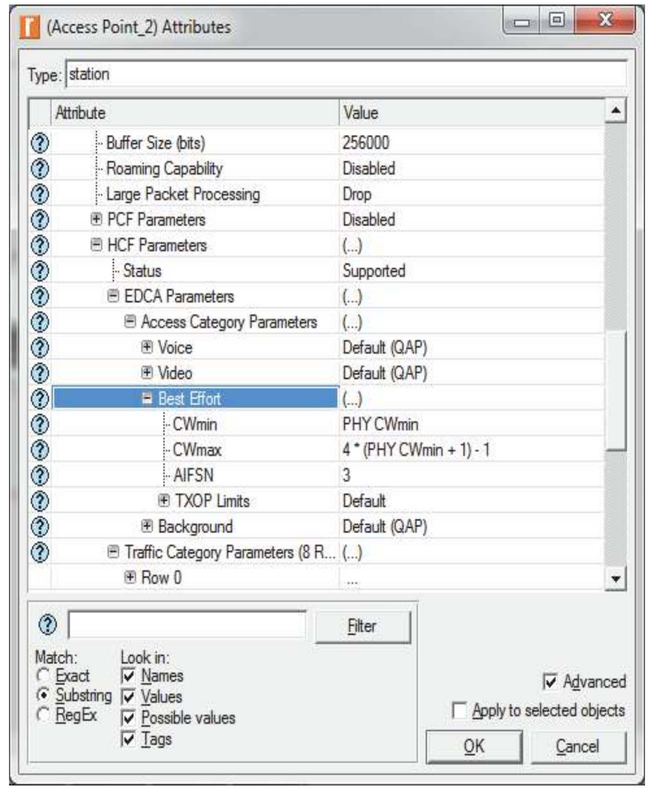

Figure 32: Default values of CWmin and CWmax.

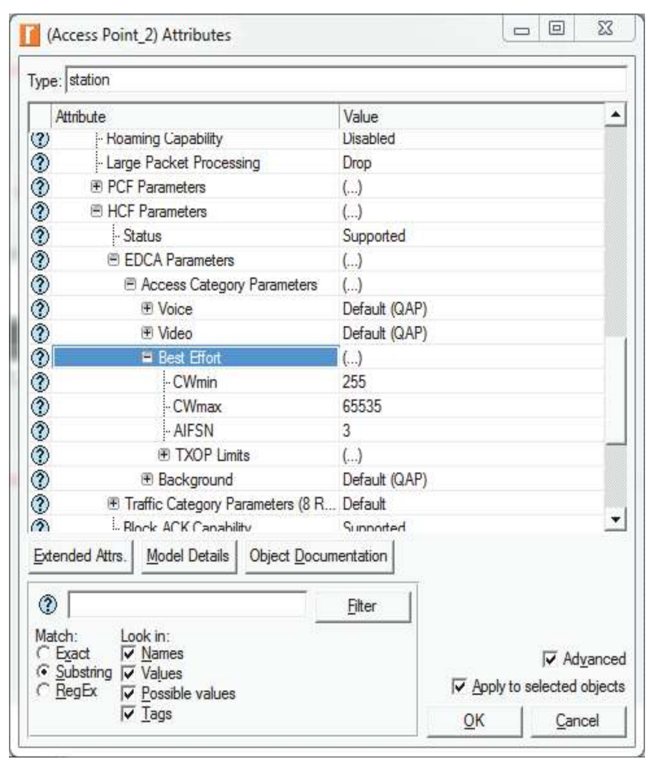

Figure 33: Optimized values of CWmin and CWmax.

A joint optimization of parameters is performed to observe the effect of various parameters on network throughput and delay. Network is designed using IEEE 802.11n standard due to its higher data rates and PHY-MAC enhancements such as block acknowledgement and frame aggregation parameters. Diverse set of results can be obtained by considering the various versions of IEEE 802.11 standard. The preeminent results have been obtained through joint parameter optimization using OPNET. The theoretical implications of optimized parameters are depicted in [17]. Wang and Wei have obtained

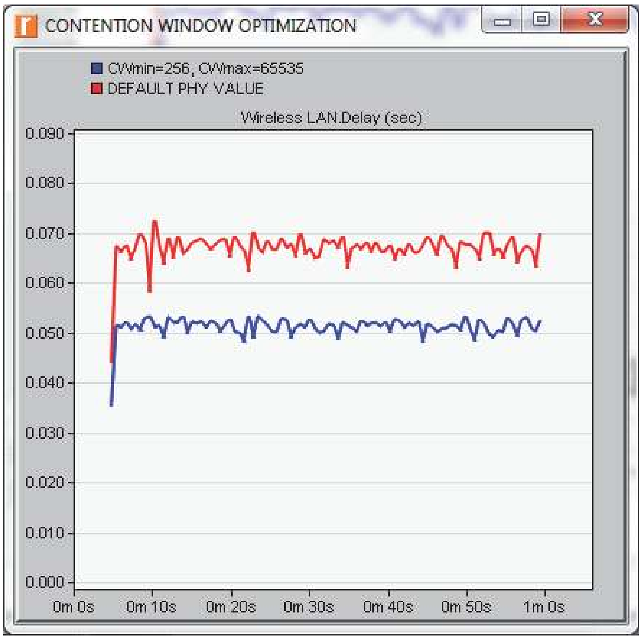

FIGURE 34: WLAN delay with and without Contention Window optimization.

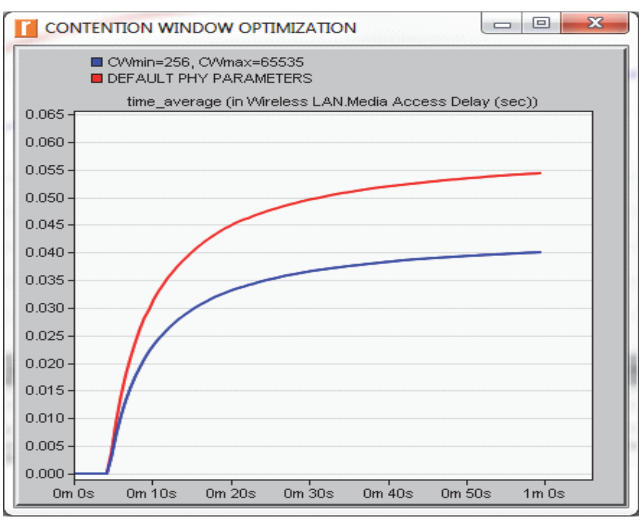

FIGURE 35: WLAN media access delay with and without Contention Window optimization.

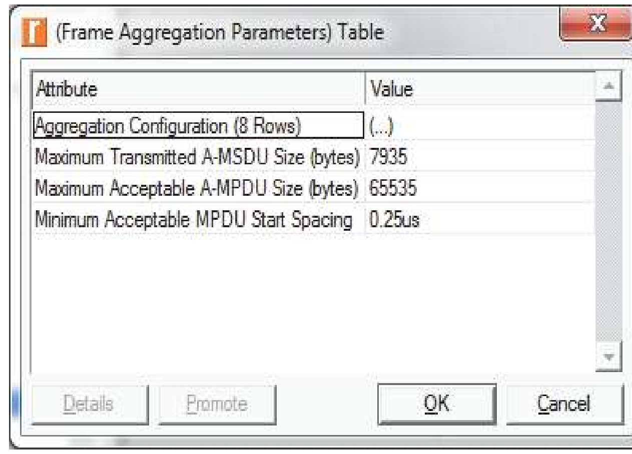

FIGURE 36: Frame aggregation parameters.

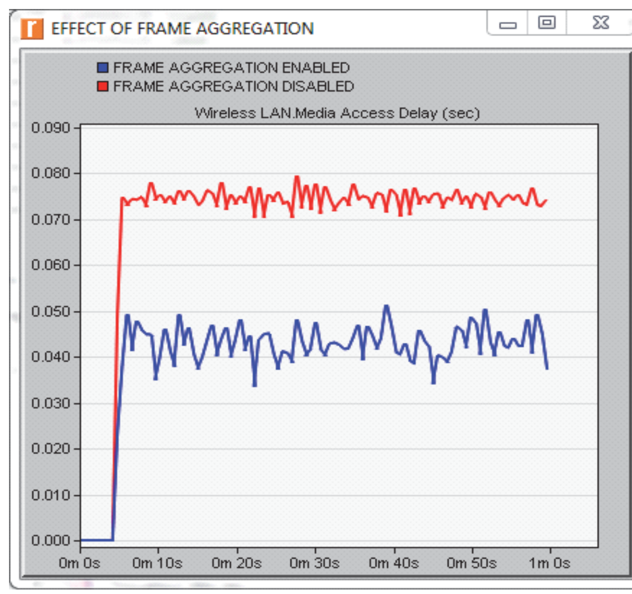

FIGURE 37: WLAN media access delay with and without frame aggregation.

improved results for IEEE 802.11n through MAC enhancement using NS-2 simulator as depicted in [18]. Performance evaluation of IEEE 802.11 standard is depicted in [19] using NS-3 simulator. Comparison of obtained results with the results derived using different simulator for same standard is considered as a validation strategy. This paper includes a novel network design using OPNET RIVERBED modeler with IEEE 802.11n standard for Smart Grid applications. The network performance can be enhanced through optimization of various parameters. The results show that some parameters have positive as well as negative effect on network performance. For example, frame aggregation reduces delay but the throughput is also reduced. To overcome this effect, frame aggregation is used with RTS and fragmentation mechanisms.

The results depict that this combination significantly improves network performance. Higher value of buffer size significantly increases throughput but the delay is also increased and thus the choice of optimum value is inevitable for network performance optimization. The simulation results are also obtained for WLAN throughput by considering an effect of distinct parameters. The work can be extended by considering different versions of IEEE 802.11 standard as well as different network designs.

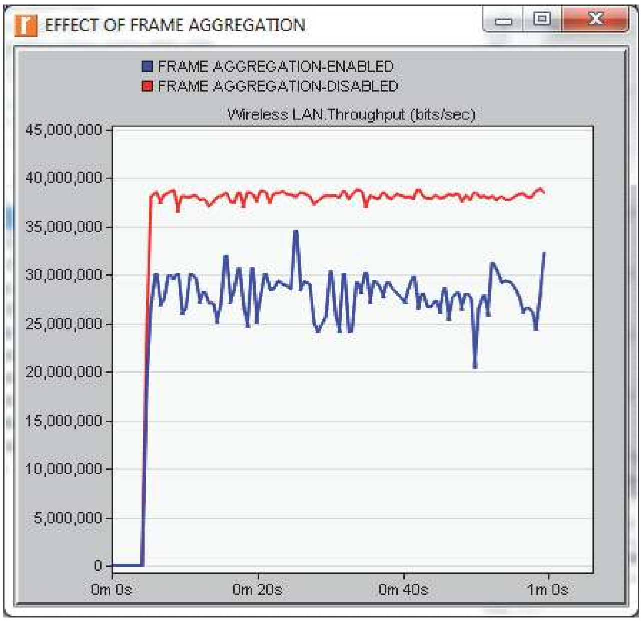

Figure 38: WLAN throughput with and without frame aggregation.

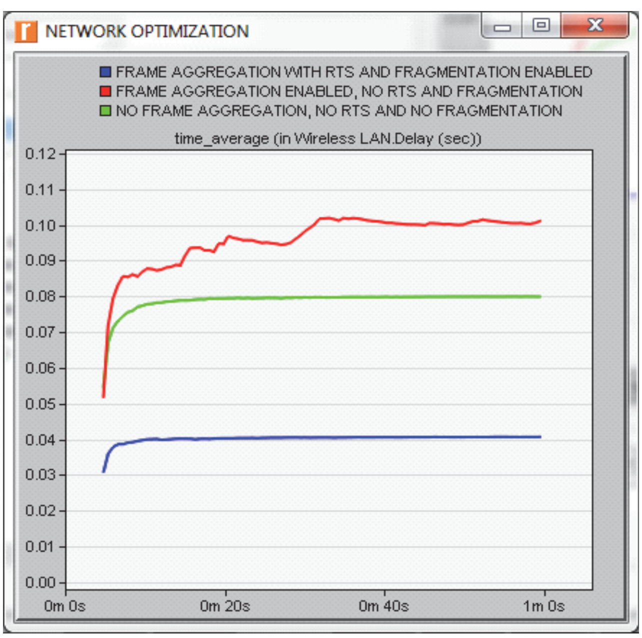

Figure 39: WLAN delay with and without RTS and fragmentation mechanisms.

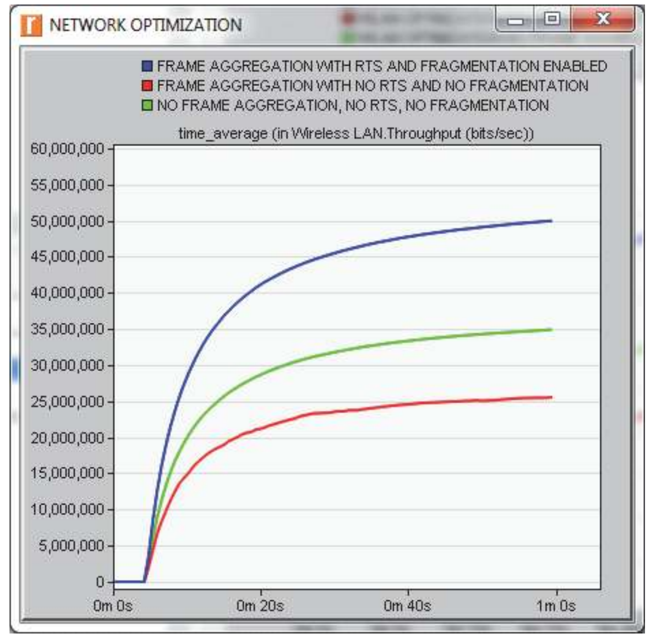

Figure 40: WLAN throughput with and without RTS and fragmentation mechanisms.

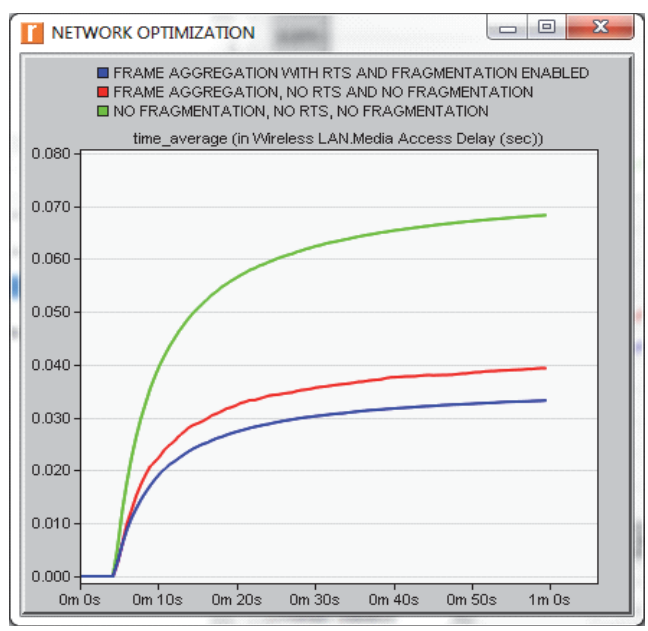

Figure 41: WLAN media access delay with and without RTS and fragmentation mechanisms.

4. Conclusion

Smart Grid is the most revolutionary technology of the present era. It is an amalgamation of electrical and ICT infrastructure. Home Area Network is meant for consumer premises. Various communication protocols such as Zigbee, Bluetooth, WLAN, and WiMAX can be used for HAN. Complex architecture of Smart Grid network necessitates optimization of various parameters of communication protocols for network performance enhancement. The primitive layered approach being used for existing communication networks cannot serve the requirements of complex Smart Grid network. Moreover, the cross layer or joint optimization of various Smart Grid communication networks is a multifaceted and challenging task as Smart Grid design is a unique approach. In this paper, the authors have described simulation results for HAN using IEEE 802.11n standard. An effect of various parameters is depicted and, finally, a novel

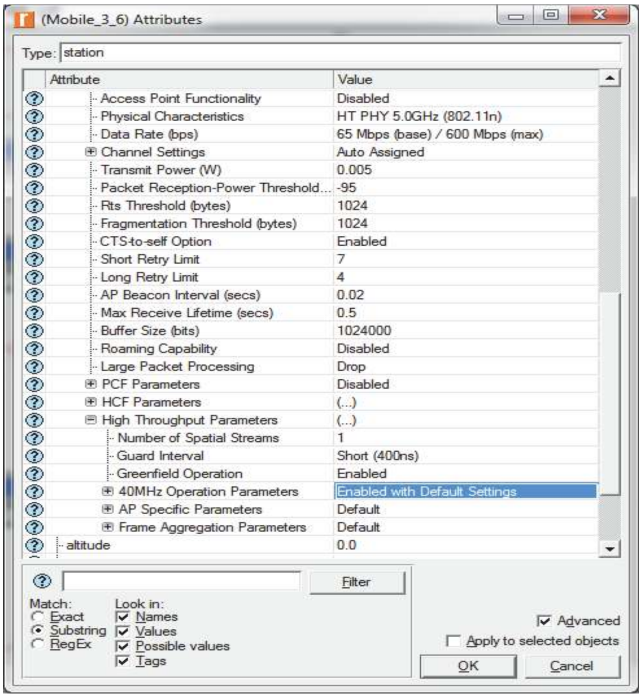

Figure 42: Values of various parameters.

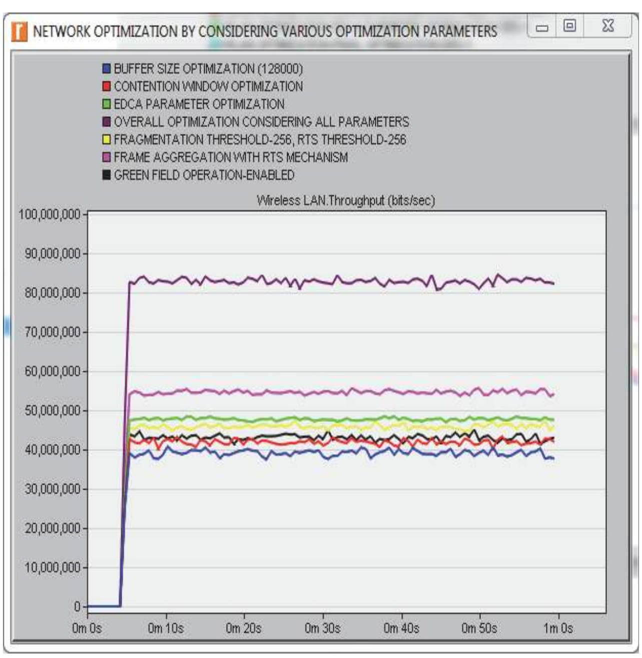

Figure 43: Network optimization by considering various parameters.

combination of parameters for performance enhancement has emerged from the simulation results. The network performance can also be evaluated for different versions of IEEE 802.11 standard which will present distinct values of results for diverse set of parameter optimization.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

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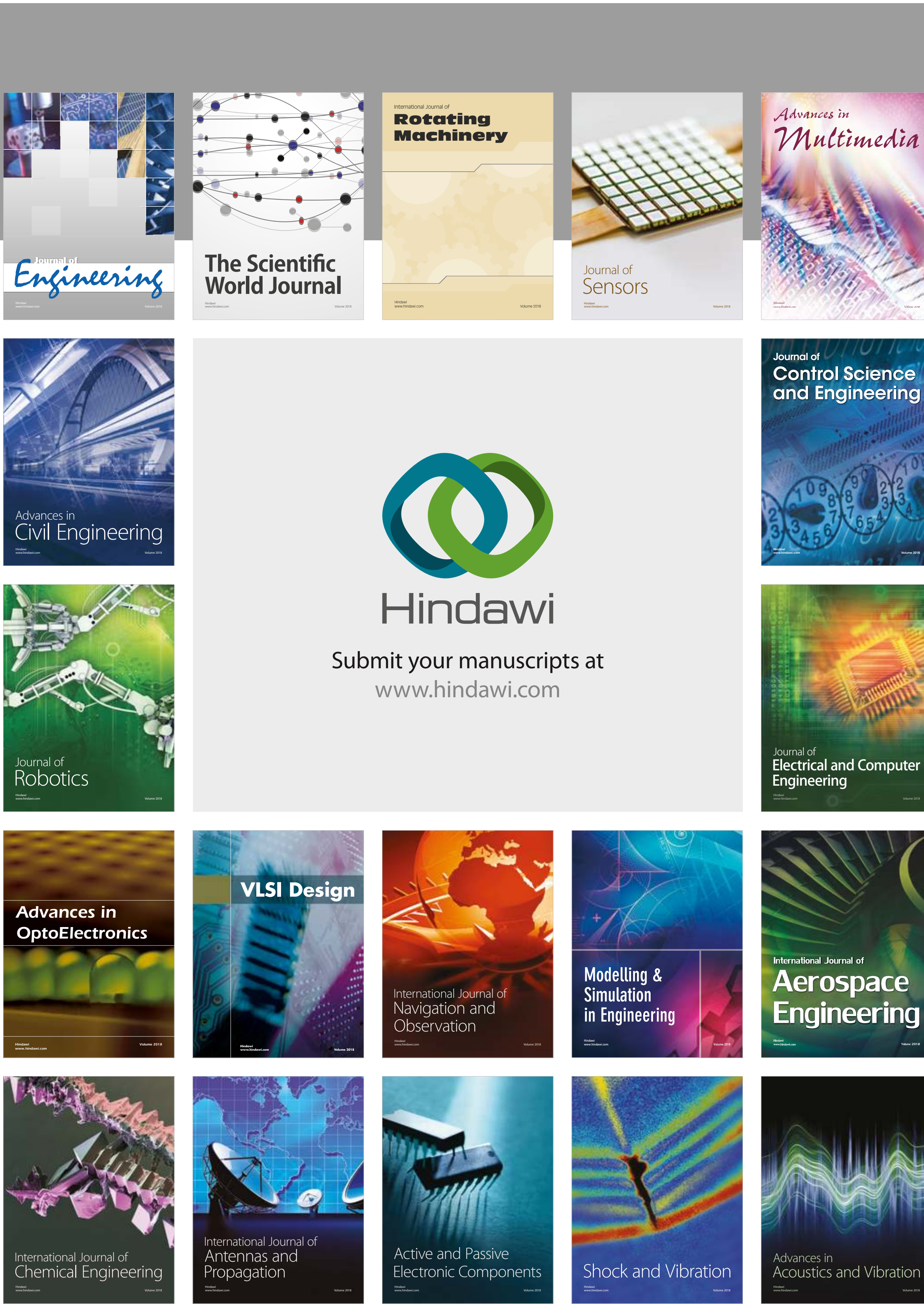
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