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RESEARCH ARTICLE

Performance Analysis of MAC Layer Protocols for WSN with Considering the Effects of Hidden Node Problem

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ABSTRACT

In this paper, the effects of the hidden node problem in Wireless sensor networks are studied on three different MAC protocols using various field distances and various numbers of nodes. This study provides the best number of nodes to be disseminated in a specific field distance depending on the needed performance metrics. Six performance metrics are used in this study, which are Goodput, Throughput, Packet delivery ratio (PDR), Residual Energy, Average Delay, and the first and last node dead in the network. IEEE 802.11, IEEE 802.15.4, and time division multiple access (TDMA) protocols are used. Results show that TDMA gives the best energy conservation and high delay time with high PDR, while IEEE 802.11 provides the best throughput and goodput results and low delay time.

Key words: WSN, IEEE 802.11, TDMA, IEEE 802.15.4, Throughput

INTRODUCTION

Wireless sensor network (WSN) is considering a very fast-growing network. It may consist of a low number (tens) to a very large number (hundreds or thousands) of sensor nodes, which are tiny and lightweight devices with limited resources such as energy level and processing capabilities. Sensor nodes architecture consists of main components, Sensing Unit, Power Unit, Communication Unit, and Processing Unit. WSN's importance is linked to their wide applications range, such as environmental applications, military applications, agricultural applications, and industrial applications. Sensor nodes depend on the application in its dissemination. It may be statically or randomly disseminated in an observation field to sense, gather, and process specific required data. Figure 1 shows the basic architecture of WSN.

WSNs encounter many challenges in their design. Energy dissipation is the main challenge in designing WSNs. It is limited and finite in Sensor nodes. Small batteries are the main energy source in sensor nodes. These batteries have limited capacity. It is stressful to replace these batteries when the number of nodes is so large and also, when using these nodes in a military application may be to locate enemy locations, it will be impossible to replace these batteries due to the hostile environment. The main causes of energy dissipation in WSN are collisions, idle listening, and communications between sensor nodes, retransmission, overhearing, and control packet overhead. These reasons to waste energy must be alleviated by designing an efficient MAC protocol.[1] MAC layer in WSNs responsibilities is flow control, channel access, error control, and scheduling. Sensor nodes almost share one transmission channel shared among them. Collisions are the main cause of the loss of sent data. Therefore, an efficient mechanism should be applied to ensure the reliability of transmitting data. This is one of the main issues in designing an effective MAC protocol.[2] The transmission range of the sensor nodes is bounded due to its limited capabilities. Therefore, nodes could not completely sense each other in the observation field, and due to the nature of WSN in gathering and send data as wireless transmission to a specific main node (sink or base station) as shown in Figure 1, a distractive problem is appeared called hidden node problem.[3,4] The hidden node problem is one of the most affected parameters in the performance of WSNs. It mainly occurs when two nodes outrange each other send data packets

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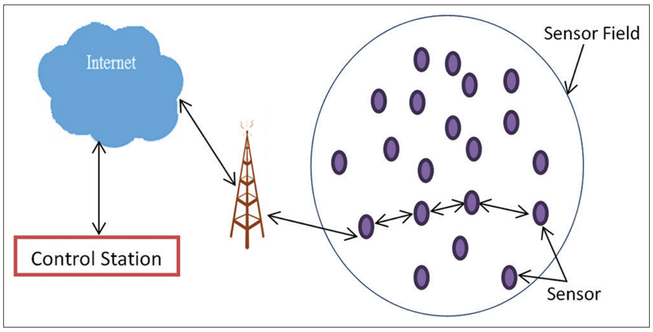

Figure 1: WSN Basic Architecture

to a third node fall in their transmission range. This leads to collision and loss of the sent packets. Furthermore, this makes sensor nodes differ their transmission for a back-off time period. Many researchers have proposed several MAC layer protocols to address or eliminate this problem, with each proposed MAC protocol having its pros and cons.[5,6]

RELATED WORK

The authors in Azad *et al*.[7] made a survey of schedule-based MAC protocols in WSNs. They introduced the MAC layer properties and the challenges of schedule-based MAC protocol. They described nine schedule-based MAC protocols. They brief their work with a comprehensive table for the used MAC protocol with listing their advantage and disadvantage. Their motivation was to give a survey on these MAC protocols for the ease of knowing their properties and the selecting of the best one for a specific application. The authors in Boudour *et al*.,[8] present the advantages of reservation-based MAC protocols and compare them with contention-based MAC protocols, especially the IEEE 802.11e standard. They simulated (RCSMA, CATA, FPRP, and IEEE 802.11e) MAC protocols using NS2. They also provide a detailed analysis of the main drawbacks and challenging issues. They found that reservation MAC protocols perform well in static ad hoc networks. Simulation results show that these protocols outperform the IEEE 802.11e standard in low mobility scenarios, but the performances of these protocols are expected to degrade as the mobility of nodes increases. Furthermore, they found that collisions could happen in reservation MAC protocol at the time of the network initialization. Finally, they found that contention-based MAC protocol suffering from high control packet overhead. The authors in Bradai *et al*.[9] present a deep and comprehensive WBAN MAC protocols performance. They evaluated the effectiveness of three MAC protocols (IEEE802.15.4, IEEE80.2.15.6, and TMAC) and conclude a better access mechanism to be used in WBAN networks. They used OMNET++ with Castalia to simulate the proposed scenarios. They run several simulations with different parameters each time. Packet delivery ratio (PDR) and latency are the used performance metrics. They simulate two scenarios, the first one for calculating the latency and the second for calculating PDR. They have evaluated these two metrics in GTS ON configuration and GTS OFF configuration. They concluded that the three protocols perform better with GTS ON the hybrid MAC protocols are better ones.

MAC LAYER PROTOCOL IN WSNs

The medium access control protocol is the most important layer in WSN since sensor nodes need self-organization capability, and self-healing when the network topology changes. The Main responsibility of MAC protocol is how to access the transmission channels. So that network resources must be fairly shared like transmission channel to increase reliability and efficiency of the network. MAC is also responsible for scheduling, buffer management, flow control, and error control. Energy is the main design issue in MAC protocol that must be given a high priority.[10] Three MAC protocols were studied in this paper which are IEEE 802.11, IEEE 802.15.4, and time division multiple access (TDMA).

IEEE 802.11

IEEE 802.11 is the standard for WLAN. It is a contention-based MAC protocol. It adopts a powerful mechanism to alleviate the hidden node problem. The fundamental mechanism it uses to access the channel is distributed coordination function (DCF), which is a random access scheme that utilizes carrier sense multiple accesses with collision avoidance (CSMA/CA) with binary exponential back-off time as its basic rule to access the transmission channel. It also supports an optional access mechanism called the point coordination function, which supports centralized and collision-free services.[11]

DCF defines two channel access techniques. The first one is called the basic access mechanism. In this technique node that has a packet to send will sense the channel if it is idle the node will wait for a period of time called distributed inter-frame space (DIFS) if the channel is still idle the node sends its packet to the destination, after successfully receiving of the sent packet the destination node waits for a short period of time called short inter-frame space (SIFS) if the channel is still idle the destination node reply with acknowledgment packet (ACK) to inform the sender with successfully data reception.[12] Figure 2 shows the basic access mechanism.

DCF also defines a more complex technique for nodes to win the transmission channel which required four-way handshaking (RTS, CTS, DATA, and ACK). The node that wants to send its packet must sense the channel to be idle and waiting for a DIFS time period if the channel is still idle, the node will send the request to send a packet (RTS), the destination upon successfully receiving and waiting for SIFS will answer with clear to send a packet (CTS). At this time, the sender and after waiting for SIFS time can send its data packet to the destination with successfully receiving wait for SIFS and send ACK packet. If the channel is sensed to be busy at DIFS waiting for the time the node will defer its transmission and wait until the channel is free again, if it is the node will wait for DIFS and generating a random back-off time to wait for before sending a data packet. This is the collision avoidance mechanism the IEEE 802.11 follows.[13] Figure 3 shows RTS, CTS mechanism.

DCF techniques also provide a virtual sensing mechanism with the use network allocation vector (NAV) to suppress other nodes from sending or receiving. NAV containing the time needed for the current transmission to be complete.

IEEE 802.15.4

IEEE 802.15.4 is considered a standard for low data rate wireless personal area networks. It defines both PHY and MAC layers. It is basic for Zigbee networks. The PHY layer features are deactivation and activation of the radio transceiver, energy detection, link quality indicator, clear channel assessment, channel selection, and transmitting and receiving packets.

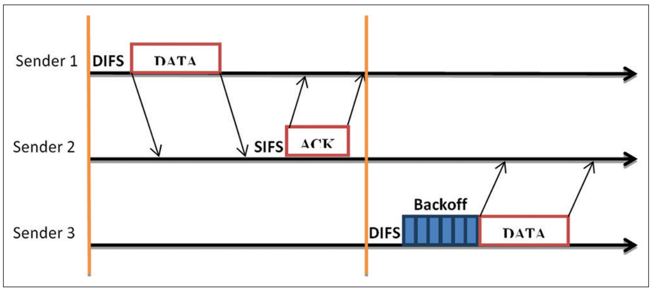

Figure 2: IEEE 802.11 Basic Access Techniques

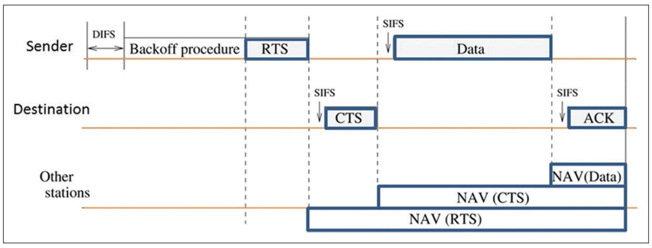

Figure 3: IEEE 802.11 DCF with RTC and CTS

The radio could be operated with these three types of bands 868–868.6 MHz, 902–928 MHz, and 2400–2483.5 MHz. The MAC sub-layer features are channel access, acknowledged frame delivery, GTS management, beacon management, disassociation, and association.[14]

IEEE 802.15.4 supports different network topologies (star, cluster tree, and mesh) and devices. An optional super frame can be used to control the duty cycle of devices. It can be used as a contention-based and scheduled-based MAC protocol. It can work with a high number of devices (65.536 devices when using short addresses [16 bits]).[15]

Two types of devices are defined in this protocol depending on their capability and complexity. Full function devices (FFD) are devices that can support all specifications of IEEE 802.15.4. It can route, relay packets, and communicate with all other devices in the network. It can be a router, coordinator, or normal (end) device. Reduced function devices are simple devices with limited capabilities that can communicate with (FFD) only.[16]

IEEE 802.15.4 can operate in two modes beacon and non-beacon. In the beacon mode, devices synchronized with the coordinator and wait for its beacon signal. To know when to go to sleep and the next beacon signal, devices use slotted CSMA/CA to compete with each other. In this mode, all devices know when to communicate with each other. The timing to wakes up must be very accurate to catch a beacon signal. Figure 4 shows communication between coordinator and network device. IEEE 802.15.4 channel access mechanism is reduced greatly when high data traffic exists in networks.[17]

In non-beacon mode devices uses unslotted CSMA/CA to contend with each other. There is no synchronization between devices. Figure 5 shows communication between the coordinator and network devices in non-beacon mode.

IEEE 802.15.4 does not apply any mechanism to alleviate the hidden node problem. This may greatly degrade the network performance due to the high collision rate.[18]

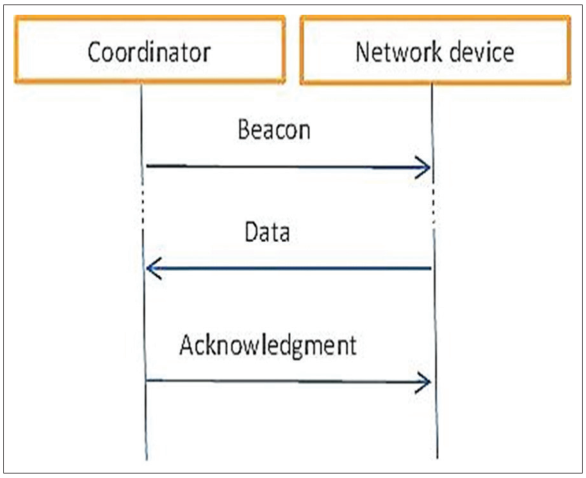

Figure 4: Communication with Coordinator in Beacon Mode

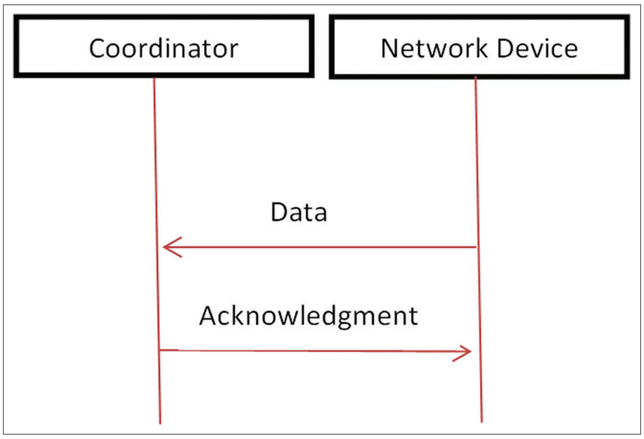

Figure 5: Communication with Coordinator in Non-Beacon Mode

TDMA

A schedule-based MAC protocol guarantees the fair distribution of transmission channels between nodes. It divides the transmission channel into equal time slots and allocates each node with a one-time slot. In this way, there is only one node that sends or receives on the transmission channel at any time. Node triggers its radio on in its allocated time slots and turns it off in the other time slots. This leads to a level of energy conservation.[19] Figure 6 shows the TDMA MAC protocol.

TDMA does not suffer from hidden nodes problem and eliminate packet collisions in the network. No idle listening for nodes since nodes turns their radio on only when it has a packet to send or receive. Allocated time slots altogether form TDMA frame which is continuously repeated.[20]

TDMA drawbacks when the number of nodes is large latency are greatly increased since the node that wants to send data packet needs to wait for the channel to have its allocated time slot. Furthermore, network bandwidth may be unutilized efficiently since some nodes may not have anything to send.[21]

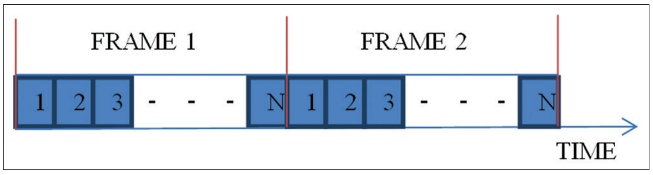

Figure 6: TDMA MAC Protocol

HIDDEN NODE PROBLEM IN WSNs

Wireless communications have a broadcast nature that all neighboring devices could hear but not all of them could interpret. This nature exhausts network resources and mainly network bandwidth. WSNs with their limited capabilities may have only one channel to send and receive data packets. This means that only one node can send data with its transmission range. The hidden node problem is the main degradation parameter in wireless networks.[22] It occurs when a node cannot sense an ongoing data transmission and send its data at the same time which leads to data collision and loss of the transmitted packets. Figure 7 illustrates hidden node problem occurrence. Node A can sense node B since it is in its radio range but cannot sense node C because it lies outside its radio range. The same is for node C; it can sense node B but cannot sense node A for the same reasons. When node A has a packet and wanting to send it to node B, it will sense and find the channel idle (no transmission is happening), so that it will start sending its packet, if before the end of A's transmission node C have a packet and want to send it to node B it will sense and find the transmission channel idle (since it

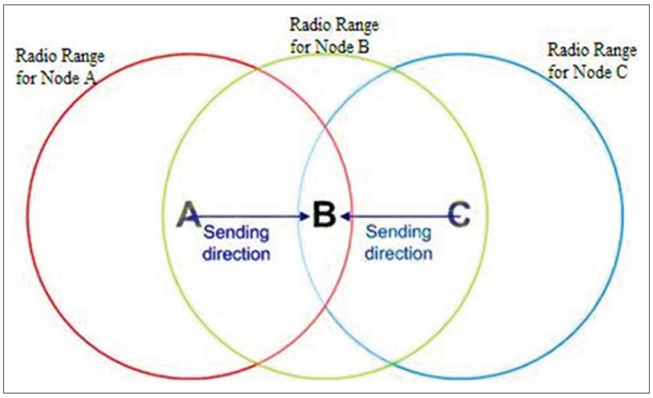

Figure 7: Hidden Node Problem

could not sense node A transmission), so that it will send its packet which leads to data collision in node B. This situation is called a hidden node or blind node problem.[23,24]

SIMULATION AND RESULTS COMPARISON

The selected MAC protocols have different properties and mechanisms to alleviate hidden node problems and to access channels, except IEEE 802.15.4 which does not provide any mechanism to alleviate hidden node problems. Simulation results from a comparison among protocols are studied to identify the characteristic of each protocol with six performance metrics (Throughput, Goodput, PDR, Delay, Average Residual Energy, and First - Last Nodes Dead). Eight scenarios are implemented with variable node number (75 and 100) and field area (250 × 250, 500 × 500, 750 × 750, and 1000 × 1000) m^2, which have been grouped into two scenarios for the simplicity of results comparison. Table 1 shows implemented scenarios.

Simulation system parameters are shown in Table 2.

Table 1: Implemented scenarios

Parameters	First Scenario	Second Scenario
Number of Nodes	75	100
Field Distance (m^2)	250, 500, 750, 1000	250, 500, 750, 1000
Simulation Time (Sec)	1000	1000
Initial Energy For Sink Node	unlimited	unlimited
Packet Source Nodes (Joule)	unlimited	unlimited
Initial Energy For Normal Nodes	2 joule	2 joule
Routing Protocol	AODV	AODV
Propagation Model	Two Ray Ground	Two Ray Ground
Tx Power (Watt)	0.0522	0.0522
Rx Power (Watt)	0.0591	0.0591
Idle Power (Watt)	0.00006	0.00006
Sleep Power (Watt)	0.000003	0.000003
Antenna	Omni Antenna	Omni Antenna

Table 2: System parameters

Simulation System	
Operating System	Ubuntu 18.04
Mobility Model	Constant Position
Packet Size	64 Byte
Type of Traffic	CBR
Traffic Rate (Kbps)	20
Interface Queue Type	PriQueue
Interface Queue Length	100000 Packet
Transport Protocol	UDP
Topology	Random
Energy Model	Energy Model in NS2
Transmission Range	250 m

The first scenario

In this scenario, (75) nodes are randomly disseminated and the field distance is varying to (250 × 250, 500 × 500, 750 × 750, and 1000 × 1000) m^2. Average results are combined and discussed for the selected protocols.

IEEE 802.11 is the dominant protocol with high throughput and goodput because of its good mechanism to alleviate hidden node problems and no sleep periods are introduced. IEEE 802.15.4 experiences high difficulties in its mechanism to access the channel when a high data rate and a high number of nodes exist. Furthermore, when field distance is increased this causes the existence of hidden node problem and the need for multi-hop to transmit data packets to sink node. TDMA generates low throughput and goodput because the increase in node number introduces high delay time. Throughput and goodput are shown in Figures 8 and 9, respectively.

PDR is shown in Figure 10. When field distance is (250 × 250) m^2 IEEE 802.11, and TDMA protocols give high results because there is no hidden node problem and no multi-hop respectively. When field distance increases IEEE 802.11 is heavily affected by hidden node problems and starts to degrade in its work. TDMA also starts to degrade because of the existence of multi-hop transmission that means more delay time and ending of simulation time

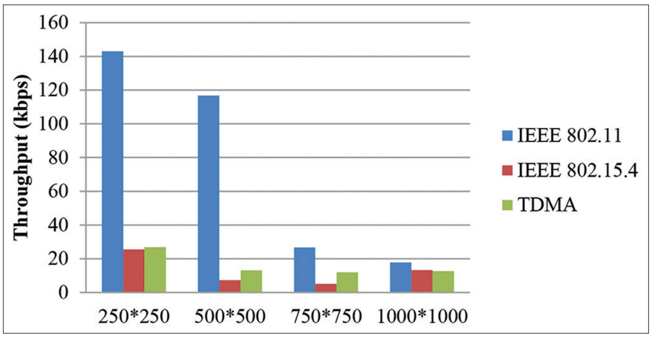

Figure 8: Throughput of first scenario in case 75 nodes

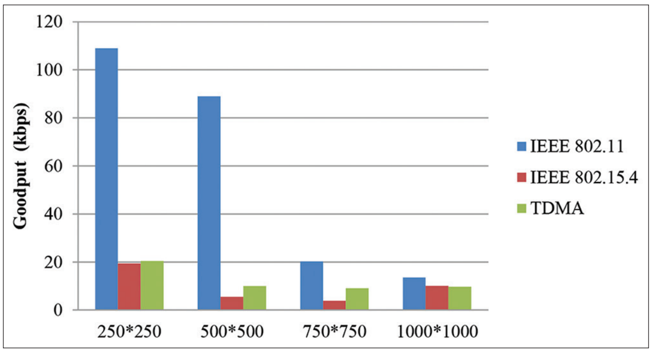

Figure 9: Goodput of first scenario in case 75 nodes

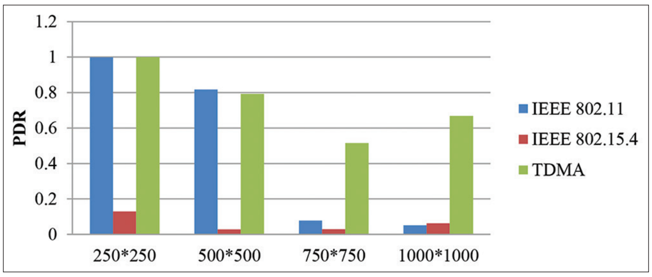

Figure 10: PDR of first scenario in case 75 nodes

with the low number of the packet transmitted. IEEE 802.15.4 PDR is very low because it cannot deal with high data rate and have no mechanism to alleviate hidden node problem.

Whenever a number of nodes increase delay time of TDMA protocol is increasing too and also when field distance increases delay times increase because of the need for more hops to reach the sink node as shown in Figure 11. When field distance is (500 × 500) m^2, high delay is shown because there was a bottleneck node in routes of two packet source nodes. IEEE 802.11 and IEEE 802.15.4 have low delay times since no sleep periods exist and no waiting for a specific time to acquire the transmission channel.

The average residual energy is shown in Figure 12. TDMA is the best protocol in energy saving since it does not suffer from collisions, idle listening, overhearing, and hidden node problem. IEEE 802.15.4 shows high residual energy since

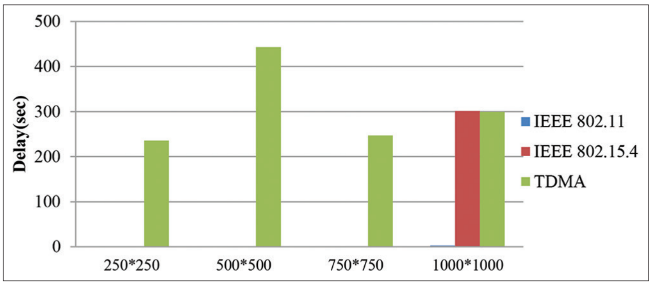

Figure 11: Average delay of first scenario in case 75 nodes

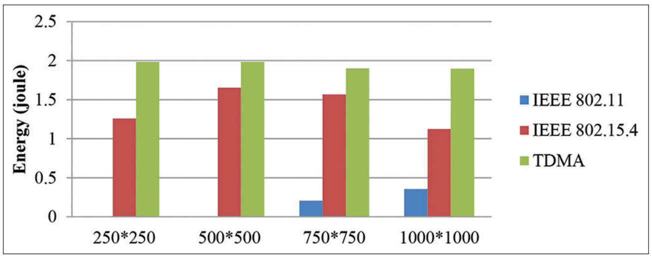

Figure 12: Average residual energy of first scenario in case 75 nodes

its throughput value is low. It has been noticed a volatile behavior for IEEE 802.15.4 protocol in its results and this because of the way it is used to access the channel. IEEE 802.11 is the worst protocol in energy conservation since it does not let nodes go to sleep and suffering from idle listening, overhearing, and hidden node problems. When field distance is (750 × 750, 1000 × 1000) m^2, IEEE 802.11 starts to save some energy and this is because some nodes do not participate in sending or receiving processes due to their location or that it is does not have a route to sink node.

The first dead and last dead nodes are shown in Figures 13 and 14. IEEE 802.11 consumes energy quickly and TDMA conserves energy very well. IEEE 802.15.4 shows volatile results because of the mechanism it implements to acquire transmission channels.

Results of the first scenario are summarized in Table 3.

The second scenario

In this scenario, (100) nodes are randomly disseminated and the field distance is varying to (250 × 250, 500 × 500, 750 × 750, and 1000 × 1000) m^2. Average results are combined and discussed for the selected protocols.

Throughput and goodput are shown in Figures 15 and 16, respectively. Almost the same results as the first scenario are obtained for the

Table 3: Summary of first scenario results in case 75 nodes

Protocol	No. of nodes	Area	Throughput (kbps)	Goodput (kbps)	Delay (sec)	PDR	Residual Energy
IEEE 802.11	75	250 × 250	143.0078	108.958	0.005411298	0.9996762	0
IEEE 802.15.4			25.50268	19.432	0.04364712	0.12959668	1.2604062
TDMA			26.8375	20.45	235.6434	1	1.983782
IEEE 802.11		500 × 500	116.8398	89.022	0.141453	0.8167504	0
IEEE 802.15.4			7.3236722	5.558	0.19836258	0.027636446	1.6543516
TDMA			13.16694	10.028	442.6296	0.7927022	1.9834266
IEEE 802.11		750 × 750	26.61642	20.278	0.8094752	0.0778876	0.2060898
IEEE 802.15.4			5.1217416	3.9	0.4769405	0.028778488	1.568578
TDMA			11.992072	9.136	247.26422	0.51611746	1.9018842
IEEE 802.11		1000 × 1000	17.79586	13.562	2.970458	0.05122306	0.354244
IEEE 802.15.4			13.220204	10.072	301.27296	0.06292734	1.1230848
TDMA			12.738388	9.704	299.1092	0.6683056	1.8996188

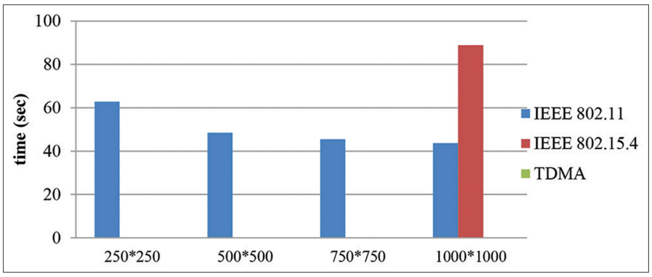

Figure 13: First dead node of first scenario in case 75 nodes

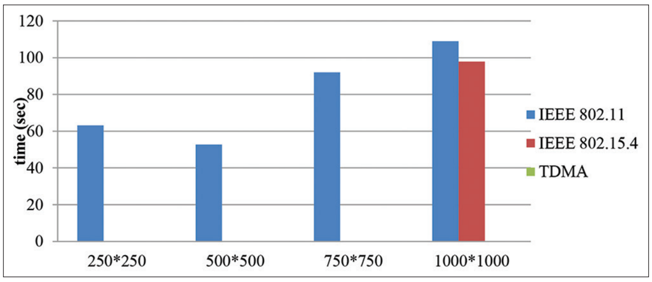

Figure 14: Last dead node of first scenario in case 75 nodes

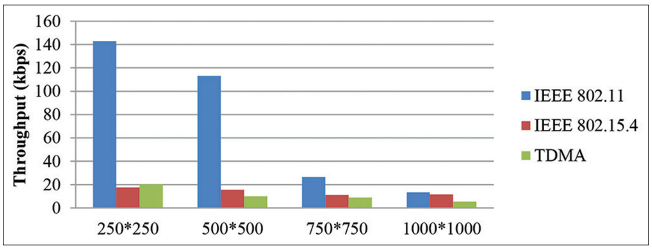

Figure 15: Throughput of second scenario in case 100 nodes

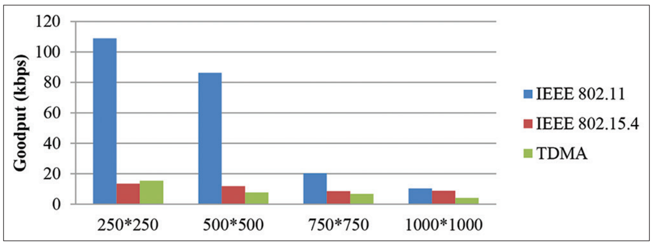

Figure 16: Goodput of second scenario in case 100 nodes

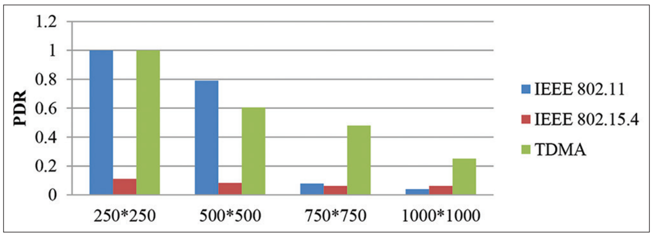

Figure 17: PDR of second scenario in case 100 nodes

same reasons mentioned before. Except that IEEE 802.15.4 performs better than TDMA because of the increase in node number and the high delay time that TDMA protocol introduces.

Figure 17 shows the PDR of the second scenario. IEEE 802.11 shows better results when field distance (250 × 250) m^2 and (500 × 500) m^2 where TDMA suffering from high delay time. When field distance increases to (750 × 750) m^2 and (1000 × 1000) m^2 IEEE 802.11 suffering from hidden node problem which degrades the protocol performance, while TDMA does not suffer from hidden node problem so that it gives the best results. IEEE 802.15.4 gives the worst PDR for the same reasons mentioned before.

The average delay is shown in Figure 18. High delay is shown for TDMA protocol and low delay for IEEE 802.11 and IEEE 802.15.4 for the same reason mentioned in the first scenario.

Average residual energy is shown in Figure 19, TDMA is the best protocol that saves energy. For the same reasons mentioned before. IEEE 802.11 is the worst protocol in energy conservation since nodes either transmit or listen for transmissions. IEEE 802.15.4 takes second place in saving energy since it gives low throughput and goodput values. And also some nodes do not participate

Table 4: Results of second scenario in case 100 nodes

Protocol	No. of nodes	Area	Throughput (kbps)	Goodput (kbps)	Delay (sec)	PDR	Residual Energy
IEEE 802.11	100	250 × 250	142.846	108.972	0.0054	0.99981	0
IEEE 802.15.4			17.5957	13.408	0.05194	0.1104	1.2713958
TDMA			20.262	15.44	326.735	1	1.97981
IEEE 802.11		500 × 500	113.241	86.28	0.15418	0.79159	0
IEEE 802.15.4			15.5622	11.856	0.14886	0.08233	1.232971
TDMA			10.0627	7.67	446.421	0.60583	1.982932
Protocol		**Area**	**Throughput (kbps)**	**Goodput (kbps)**	**Delay (sec)**	**PDR**	**Residual Energy**
IEEE 802.11		750 × 750	26.4629	20.162	0.81136	0.0791	0.240972
IEEE 802.15.4			11.1121	8.466	0.20536	0.06236	0.9774928
TDMA			8.86032	6.75	304.843	0.48007	1.8389896
IEEE 802.11		1000 × 1000	13.4518	10.252	2.6041	0.03995	0.3121508
IEEE 802.15.4			11.5979	8.834	0.25746	0.0631	1.2270214
TDMA			5.35951	4.082	220.765	0.25111	1.8938288

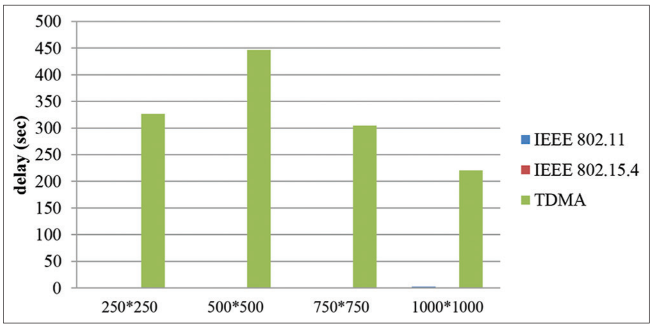

Figure 18: Average delay of second scenario in case 100 nodes

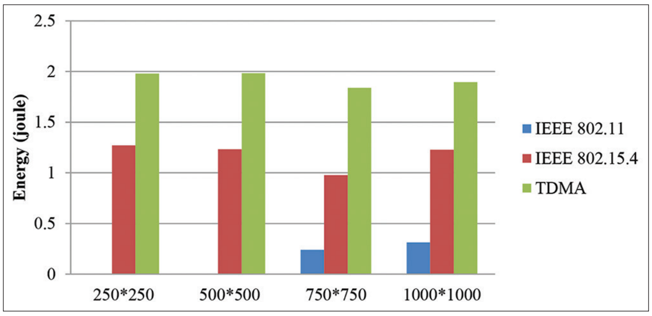

Figure 19: Average residual energy of second scenario in case 100 nodes

in data transmission because they have no route to sink node that makes them lose energy only by idle listening. This is the same case for IEEE 802.11 when field distance is (750 × 750) m^2 and (1000 × 1000) m^2.

The first and last dead nodes are shown in Figures 20 and 21, respectively. Almost, the same results as the first scenario are obtained for the same reasons mentioned before.

Summary of obtained results of the second scenario is listed in Table 4.

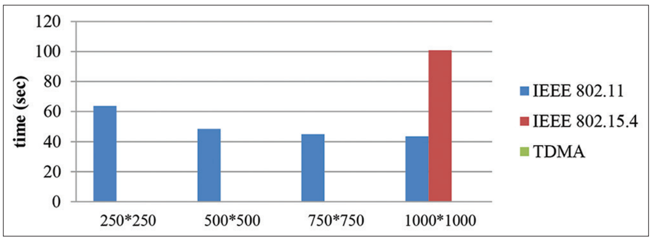

Figure 20: First dead node of second scenario in case 100 nodes

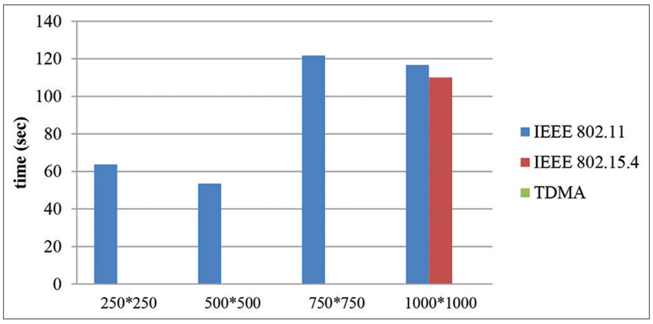

Figure 21: Last dead node of second scenario in case 100 nodes

CONCLUSION

In this paper, three MAC protocols were simulated and compared with each other using different scenarios and different performance metrics. The results show that IEEE 802.11 protocol is performing better in throughput and goodput results, and also gives low delay time. This is because IEEE 802.11 forces nodes to always be awake, which make them, have full knowledge of the status of the network. IEEE 802.15.4 is given low delay time with volatile results. While TDMA protocol performs better in energy conservation since it let nodes go to sleep and save energy and does not suffer from idle listening, overhearing, and hidden node problem. Hidden node problems have a great influence on IEEE 802.11 and IEEE 802.15.4 MAC protocols and highly degrade the network performance.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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