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DESIGN OF CAUCUS MEDIUM ACCESS CONTROL (C-MAC) PROTOCOL FOR WIRELESS SENSOR NETWORKS IN SMART GRIDS

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Abstract

A Caucus-based medium access control protocol (C-MAC) is proposed to reduce the end to end delay and battery consumption of the sensor nodes deployed in the monitoring of various smart grid regions, such as substation, pole and wires, perimeter security, real time and non-real-time monitoring using wireless sensor networks. The objective is to prolong the network lifetime and to reduce the end to end delay by mitigating the energy-hole problem and by eliminating bottlenecks significantly by using caucus based efficient synchronization techniques in multi-hop square grid topology of the wireless sensor networks (WSNs). The protocol self-reliantly and adaptively schedules node's wake-up times, decreases idle listening and collisions, increases network throughput, and extends network lifetime. It induces a low duty cycle for adjusting wake-up times of sensor nodes. The appropriate selection of active and sleep time slots and next hop relay nodes are proposed to minimize the data transmission latency and to reduce battery consumption to increase the network lifetime. The uniform and synchronized transmission of the data packets is of prime importance to improve the network performance. Simulation results justify that the proposed C-MAC protocol increases the network lifetime, successful data transmission ratio along-with the reduction in end to end delay. The objective of this paper is to envisage benefits and utilization of C-MAC protocol for WSNs deployed in smart grids and to draw the attention of researchers in this area.

Keywords: Caucus based medium access control, Network lifetime, Relay nodes, Transmission latency, Harsh environments, Smart grid.

Nomenclatures

G_i	The i^{th} number of a square grid
i	Integers from 1 to m
j	The number of a time slot
k	A sensor node which belongs to the network
N_{Gi}	The number of nodes in the i^{th} square grid layer
T_s	Total simulation time of the network, seconds
x	Integers

Greek Symbols

δ	Number of the time slots allocated in a layer
Ψ	The total number of nodes in a network
σ	Active time duration of a sensor node, s
τ	The time slot, s

Abbreviations

C-MAC	Caucus based Medium Access Control
EM-MAC	Efficient Multichannel Medium Access Control
ETAP	Electrical Transient Analyzer Program
HAN	Home Area Network
MAC	Medium Access Control
NAN	Neighbourhood Area Network
NET_INIT	Network Initialization
PAN	Personal Area Network
PW-MAC	Predictive Wakeup Medium Access Control
QMAC	Queen Medium Access Control
RC-MAC	Receiver Centric Medium Access Control
WSN	Wireless Sensor Network

1. Introduction

Wireless sensor networks have wide range of applications in smart grids, including taking an energy meter reading remotely, automatically and wirelessly; monitoring of power grid assets remotely, equipment fault diagnostics, target monitoring, etc. [1, 2]. Akyildiz et al. [2] have analysed the lifetime of wireless sensor nodes under different harsh environments in smart grid where human access during an operational plant is fatal, such as 500 kV substation, main power control room, and underground transformer vaults. Hence, it is important to quantify the impact of the harsh environments in smart grid on node's lifetime.

The lifetimes of different networks are used to evaluate by various lifetime models, such as schedule-driven and event-driven. Generally, five different power states are usually used for each lifetime model [2]. The schedule driven node has a predefined duty cycle as awake time/duty period. It is sleeping most of the time of operation and sleeps until the node's wake-up timer expires. In an event driven node, the pre-processor is always on and the node is in a deep sleep mode. It is in the active state if and only if an event is detected. Specifically, state transition overhead and communication cost, power consumption per task and a set of sensor hardware parameters, are used to calculate the sensor lifetime for a given event arrival rate. The power state transitions are described as a Semi-Markov chain [2]. Generally, the sensor nodes are battery powered and it is often not feasible to recharge or replace them. Thus, it is important to design energy-efficient protocols for WSNs [3-4].

Recently, the different strategies of sensor nodes deployment in dissimilar smart grid surroundings [5-10] routing protocols [11-16] and energy-efficient medium access control (MAC) protocols [17-19] intend to reduce the rate of depletion of battery power of sensor nodes and increase network lifetime. These wireless sensor nodes are randomly and uniformly deployed to cooperatively perform a common task. The task can be performed by constantly sending data to a single sink node which is a PAN (Personal Area Network) coordinator by the large number of sensor nodes deployed in the sensor field. In many-to-one communication model, the rate of power depletion of a sensor node is inversely proportional to its distance from the sink node [20]. To reduce the rate of power consumption by the nearby sensor nodes to the sink node, a quorum based energy saving MAC protocol (Queen-MAC) [20] has been proposed by Gholam Hossein Ekbatanifard.

There is an essential requirement of such energy-efficient MAC protocols in the rapidly evolving field of modern power grids called smart grids. In smart grids, the monitoring of important parameters and expensive assets require the continuous transmission of the real-time information from the consumer's premises to the utility (energy) provider. The recent advancements in WSNs may facilitate as future energy consumption management system. In scenarios such as harsh smart grid environments, the critical parameters can be monitored and controlled by deploying many wireless sensor nodes and by employing energy-efficient MAC protocols. In this paper, to reduce the energy consumption and to extend the network lifetime of a well-planned wireless sensor network deployed in power grids and industries a caucus-based medium access control protocol (C-MAC) is proposed. The word "caucus" means the group of sensor nodes must wake up in the same time slot. This protocol is implemented for a square grid topology in which, the group of sensor nodes has a very small active duration just sufficient to sense the information and send it to the sink node. The grid shown in Fig. 1 is made up of a distribution power grid of 1500 MVA, 500 kV substation, main power control room and underground network transformer vaults connected with buses of 11 kV and 0.415 kV.

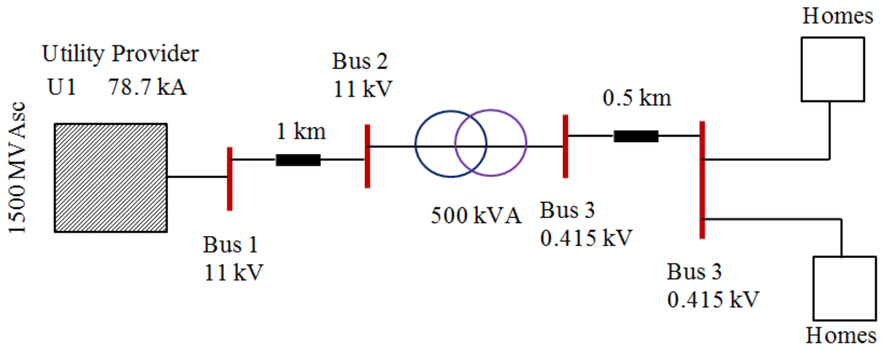

Fig. 1. The design of the power distribution grid of 1500 MVA using ETAP simulator.

The protocols QMAC [21], PW-MAC [22] and EM-MAC [23] are developed to enhance the performance of wireless sensor networks. A typical power generation and distribution grid has been verified using ETAP (Electrical Transient Analyzer Program) simulator [24], where substation, main power control room and underground transformer vaults are considered in understanding the communication architecture of the power grid. The sensor nodes in the different environments are interconnected using IEEE 802.15.4 (ZigBee) protocol having a channel frequency of 2.4 GHz and IEEE 802.11b (Wi-Fi) protocol having a channel frequency of 5 GHz to connect a sink node to the utility provider due to its fast communication capability for long distance. Few relay nodes have been implemented along with C-MAC protocol to further increase the network lifetime and to reduce the end to end delay.

The rest of this paper is arranged as follows. Section 2 discusses recent related work. In section 3, preliminaries and assumptions are described. The description and mathematical model formulated for the network is explained in section 4. Section 5 presents results of simulations and analysis. Finally, section 6 highlights the key findings from this paper as conclusion and also intimate about the future scope of the research work.

2. Related Work

A number of solutions have been proposed in the past investigating novel MAC for WSNs which however ignore problems related to medium access control. In QMAC [18], a method to allocate different grid sizes to coronas in constant traffic rate has been proposed, without stating how and when grid sizes should be altered with traffic rate variations. RC-MAC [19] is a receiver-centric MAC protocol developed for event-driven wireless sensor networks. Gholam Hossein Ekbatanifard et al. [20] has proposed and implemented QMAC (Queen-MAC) protocol for energy saving of uniformly distributed sensor nodes in WSNs. The energy used for retransmission of lost packets, collisions, idle listening and wake-up/sleep scheduling and its overhead are the major problems in the medium access control (MAC). In [20], the emphasis is on these problems and as a solution an adaptive quorum-based MAC protocol, Queen-MAC has been proposed.

As expected, the protocol decreases idle listening and collisions by the precise selection of active time slots improving the synchronization and scheduling. It also prolongs network lifetime, increases network throughput and self-reliantly and adaptively schedules nodes sleep/wake-up times. Queen-MAC is highly appropriate for real-time monitoring and data collection applications. It decides the node’s sleep and active duration according to the traffic loads, where nodes are uniformly placed within an area of radius 350 m. The simulation is conducted in a network with five groups of nodes where sensor nodes are uniformly placed. The channel capacity is 250 Kbps. Each node generates a 32-byte data packet every second. The transmission range of a sensor node is 75 m unless otherwise mentioned. A time slot is set to be 100 ms long. The energy consumption model of MICAz is employed in the simulation, where the power consumption for transmit, receive, idle, and sleep modes are 52.2 mW, 83.1 mW, 105 µW, and 48 µW, respectively. Each sensor node has an initial energy of 10 J. Each simulation run lasts 1000 s (10,000-time slots). Queen-MAC prolongs the network lifetime while increasing the average delivery ratio and keeping the transmission latency low.

Chao and Lee [21] utilize grid quorum, coronas and single channel for WSNs to achieve the longer battery lifetime in QMAC. This protocol attempts to decrease the energy consumption in sensor nodes by increasing their sleep time. However, in a network the use of a single channel leads to an increase in network energy consumption as well as latency, therefore needing packet retransmission due to an increase in collisions.

In PW-MAC [22] every sensor node calculates its active time using a pseudo-random wake-up schedule which is a receiver-initiated predictive wake-up MAC protocol. Each node broadcasts a beacon periodically to announce that it is awake and ready to receive data. A sender waits for a beacon and has to know receiver's pseudo-random generator parameters to wake up a little earlier than the receiver. However, PW-MAC has some shortcomings since each node has to send a beacon every time it wakes up regardless of whether any sender has data to send or not. In addition, protocol overhead increases as each node broadcasts its pseudo-random generator parameters periodically, which in turn deteriorates at higher network densities.

EM-MAC [23] is an asynchronous multi-channel receiver-initiated MAC protocol proposed for WSNs. In EM-MAC, a sender wake-up prior to a receiver by predicting the wake-up time and wake-up channel of the receiver. In EM-MAC like PW-MAC the sender knows the state of the receiver's pseudo-random function used to generate its wake-up channels and times. EM-MAC not only has the shortcomings of PW-MAC but also each node in EM-MAC has to invoke its pseudo-random generator twice, which bears a further overhead for the protocol. The simulators ETAP [24] and QualNet [25] are used to perform the simulations.

3. Preliminaries

In this paper, we make the following assumptions:

- All sensor nodes are time synchronized.
- Each sensor node has a unique ID.
- Sensor nodes are deployed in a square grid network area centered at the sink node. The motive behind the selection of square grid deployment is that it resembles with the architecture of a well-planned grid.
- The simulation area is divided into several concentric squares based on their hop count to the sink node at equal distances having equal number of nodes, as shown in Fig. 2. During the network-initialization phase, a control packet NET_INIT with a field hopcount = 1 is sent from the sink to create the concentric square grid layers. Upon receiving this packet, each node increases the hop count field by one and then rebroadcasts the packet.
- A node belongs to a square grid layer Gi if it receives a NET_INIT with hopcount = i. In case of multiple NET_INIT packets, only the one with the lowest hopcount value is considered. The sensor nodes in a square grid layer Gi are i hops away from the sink node and rely on the nodes in Gi-1 to relay their sensed data. The flowchart explaining the network initialization process is shown in Fig. 3.
- Sensor nodes send their data to their common sink node.
- All sensor nodes are static in nature and have the same transmission range.

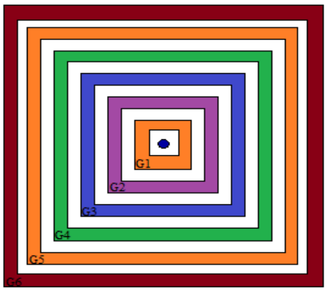

Fig. 2. The wireless sensor network divided into adjacent square grid layers centered at the sink node.

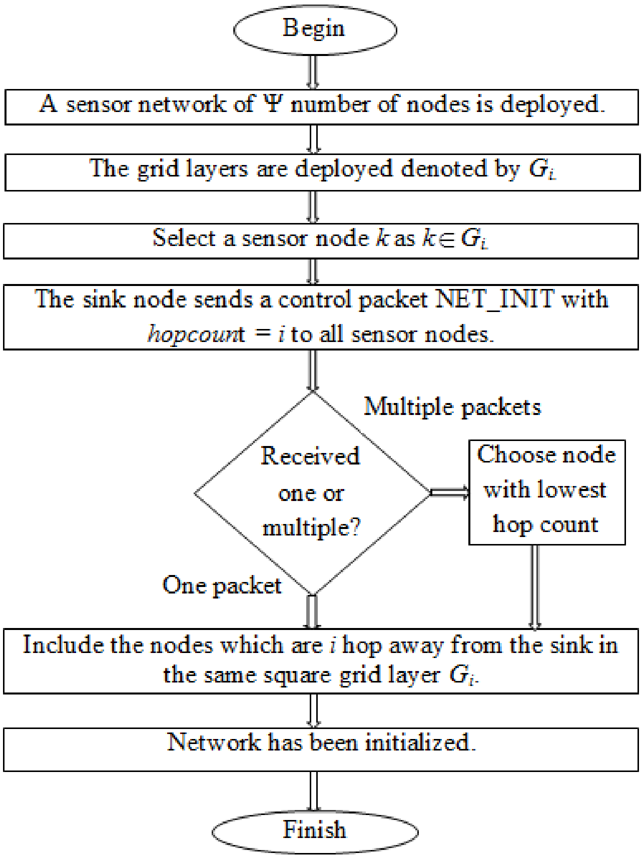

Fig. 3. The flowchart of the network initialization phase.

4. Mathematical Model

The proposed energy saving algorithm implemented in the network deployed in the smart grid is shown in Fig. 4. The different numbers of nodes are deployed while keeping the node density same in the two scenarios of 241 and 482 nodes. The symbols and meanings of the design parameters are given in Table 1.

Table 1. The design parameters.

Symbol	Meaning
Ψ	Total number of nodes in the network.
i	Integer from 1 to *m*.
G_i	The i^{th} number of square grid layer.
$\boldsymbol{k}$	A sensor node which belongs to the network.
$\boldsymbol{T_s}$	Total simulation time of the network.
N_{G_i}	Number of nodes in i^{th} square grid layer.
δ_{G_i}	Number of time slots in i^{th} square grid layer.
σ	Active time duration of the sensor node.

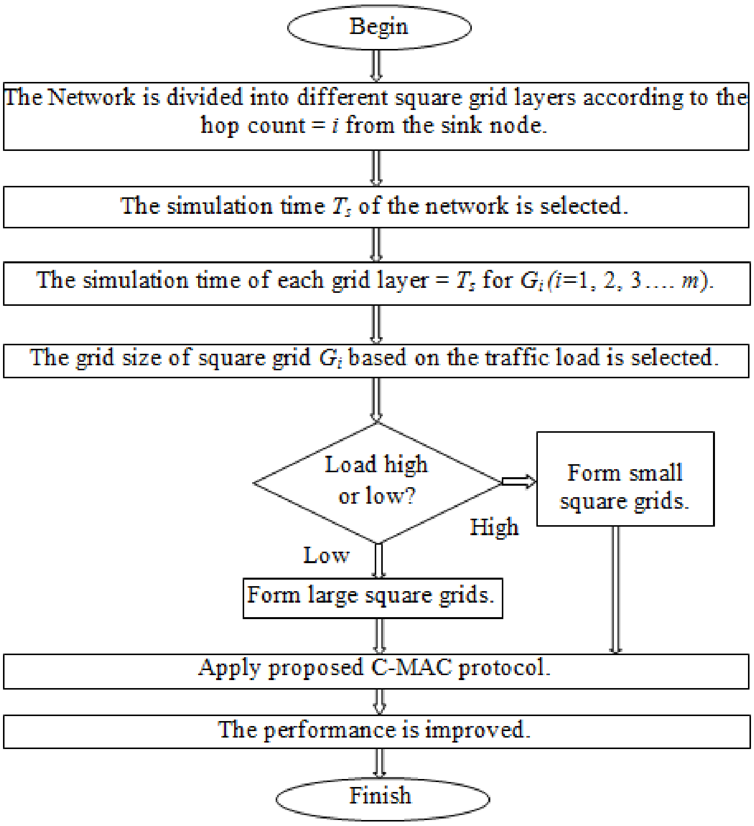

Fig. 4. The flowchart of the proposed C-MAC protocol for WSN.

After the initialization phase, the whole network is divided into numbers of concentric square grid layers assigned with a grid size according to their traffic load (closer nodes to sink are the heavy loaded ones). The distance between two nodes lying in the different grid layers is different. Let the total number of sensor nodes deployed is denoted by Ψ and formulated as shown in Eq. (1).

$$\Psi = \sum_{i=1}^{m} N_{G_i} \quad \text{where } i=1, 2, 3,\ldots, m \tag{1}$$

where N_{G_i} denotes the number of sensor nodes in the i^{th} concentric square grid layer.

The G_1, G_2, G_3...., Gi are the concentric square grid layers having equal number of sensor nodes. The optimum value of number of square grids denoted as m is 6, determined by considering the impact of path losses, contentions and traffic load. The increase in the number of grids will increase the complexity of the system by increasing the traffic load causing congestion and by increasing the number of sensor nodes competing during the contention access period to access the channel. The maximum value of square grids can be varied by considering the influence of path losses, collisions and traffic load by precisely measuring and keeping their values in the permissible limits. The total simulation time of the network is denoted as $T_{s.}$ According to the traffic load different ($r\times r$) grid sizes are assigned to the number of square grid layers. The layers closer to the sink node have higher traffic load while relaying the sensed data from the previous grid layer. So, we choose smaller grid size for the first layer as 1×1. The calculation of the number of time slots available to the nodes in the specified grid layer is expressed in Eq. (2).

$$\delta_{G_i} = i^2 \tag{2}$$

where i=1, 2, 3,…., m

For example, if i = 1 then

$\delta_{G_i} = 1 \times 1 = 1$ which means the first square grid layer has only one-time slot.

The second grid layer G_i where i=2 has 4-time slots which are distributed among all the nodes in the layer. The method of allotment of particular time slot to the sensor nodes is shown in Figs. 5 and 6, that node A and node B both pick the same time slot 0. So, both sensor nodes must wake up during the same time slot. In the same way, node C and node D have chosen the time slot 3. Both nodes meet with each other in the same time slot to share their schedule [16, 17]. The way of selection of time slots in the third layer G_3 (3×3) is shown in Figs. 7 and 8. The total numbers of time slots are i^2 = 9 in G_3. The outer square field of the grid size (3×3) has nine-time slots from 0 to 8. During the time slot 0 nodes A and B wake up leaving all other nodes in sleep mode. Likewise, node C and node D wake up during the time slot 6.

Along with the allotment of time slots, the selection of sensor nodes must wake up during active mode time slot τ_n where n is the number of the time slot is very important. It is mentioned earlier that the number of time slots allotted to the grid layer G_2 is 4 denoted as τ_0, τ_1, τ_2 and τ_3. The maximum number of time slots supported by this system is i^2 = 36 from 0 to 35, based on the maximum number of square grids, i. The sequence of sensor nodes must wake up during active mode of the G_2 layer is expressed in Eq. (3). During τ_0 the set of sensor nodes must wake up is

$$S(\tau_0) = \{(2x+1)\} \tag{3}$$

Equation (3) has described that the sensor nodes must wake up during time slot τ_0 are having sequence numbers 1, 3, 5, 7, 9, 11, 13, 15, 17 and so on. Likewise,

$$S(\tau_1) = \{(2x+2)\} \tag{4}$$

$$S(\tau_2) = \{[N_{G_i} - (2x+1)]\} \tag{5}$$

$$S(\tau_3) = \{[N_{G_i} - (2x+2)]\} \tag{6}$$

where $x = 0, 1, 2, \ldots, n$

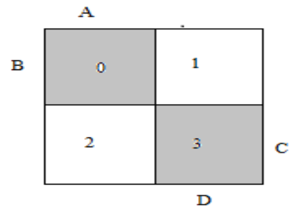

Fig. 5. The assignment of active time slots to the sensor nodes of layer G2 (2×2) of the square grid.

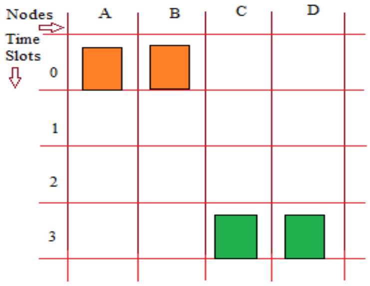

Fig. 6. The timing diagram of slot allotment for the layer G2.

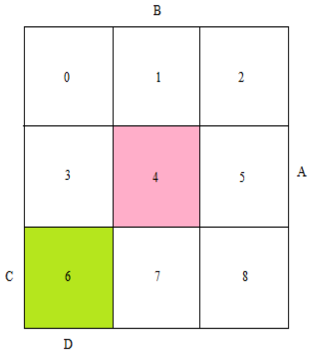

Fig. 7. The assignment of time slots to the sensor nodes of layer G3 (3×3) square grid.

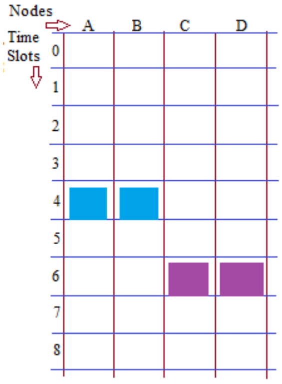

Fig. 8. The timing diagram of active time slot allotment for layer G3.

The range of the values of x is from 0 to the value which covers all the sensor nodes in the network. For the networks of 241 and 482 nodes the maximum values of x are 120 and 240 respectively. The summation of the duration of all time slots assigned to a single square grid layer is equal to the total simulation time of the network. It is equal for all layers. The sink node remains active for the complete simulation time. The time duration, during which a sensor node remains active in G_i is denoted by σ_i. The expression for σ_i is given in Eq. (7).

$$\sigma_i = \frac{T_s}{i \times i} \tag{7}$$

where $i = 1, 2, 3, \ldots, m$

The above expression interprets that large number of nodes sleeping for most of the time saves energy. The duration of the time slots in the active mode are longer for the inner layers than the outer grid layers as they have higher traffic load. The active duration of time slots σ_i increases as it proceeds towards the sink node as shown in Eq. (8).

$$\sigma_1 \succ \sigma_2 \succ \sigma_3 \succ \sigma_4 \succ \sigma_5 \succ \sigma_6 \tag{8}$$

The relation between the total simulation time of the network and the duration of active time of a sensor node in the i^{th} square grid layer G_i is exhibited as given in Eq. (9).

$$T_s = \sum_{j=0}^{j=i^2-1} \tau_j \tag{9}$$

where $i = 1, 2, 3,\ldots, m$.

For example, the value of T_s for G_i when i=3 is equal to the summation of duration of time slots from τ_0 to τ_8. The number of time slots allocated to different square grid layers is shown in Fig. 9.

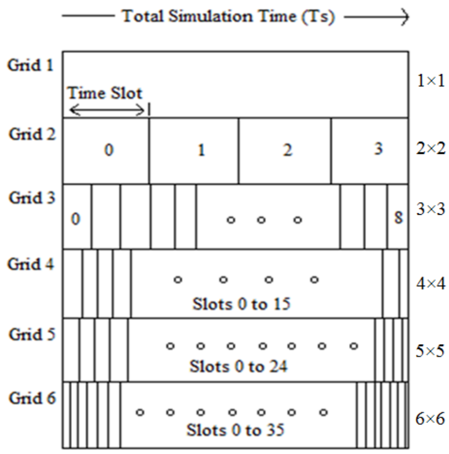

Fig. 9. The number of time slots in different layers of concentric square grids G_i.

5. Simulation Results and Analysis

To evaluate the performance of C-MAC, the simulator Qualnet 6.1 [25] is used. The complete communication architecture of the wireless sensor network used for simulations is divided into two parts (a) the monitoring area of various smart grid applications like: Advanced metering infrastructure, Power outage detection, towers and poles monitoring (non-real time monitoring) in Home Area Network (HAN) based on IEEE 802.15.4 (ZigBee) protocol using a channel frequency of 2.4 GHz and (b) a utility provider part of Neighborhood Area Network (NAN) based on IEEE 802.11b (Wi-Fi) protocol using a channel frequency of 5 GHz between PAN coordinator (sink) and the utility provider.

The purpose of deploying sensor nodes at the different smart grid areas is to load control, power system monitoring and control, fault diagnostics, power fraud detection, demand response and distribution automation. Likewise, NAN is used to send information gathered at PAN coordinator to the utility provider situated far away from it. In the simulation scenarios 241 and 482 sensor nodes are uniformly deployed as six concentric square grid layers of equal number of sensor nodes over a 100m×100m and 200m×100m area respectively, having same node densities and equal inter-nodal distance in the same grid layer. It is important to mention that the inter-nodal distance of two different square grid layers is different. The aim of the newly proposed C-MAC protocol is to prolong the network lifetime by saving the energy of sensor nodes deployed in smart grids. The network scenario of 483 sensor nodes is shown in Fig. 10 is simulated using Qualnet 6.1 simulator [25]. The network simulation parameters are given in Table 2. The PAN coordinator and the utility (energy) provider remains active for the complete simulation time T_S. The simulation results of the networks using 802.15.4, with C-MAC and with C-MAC along with relay nodes are compared.

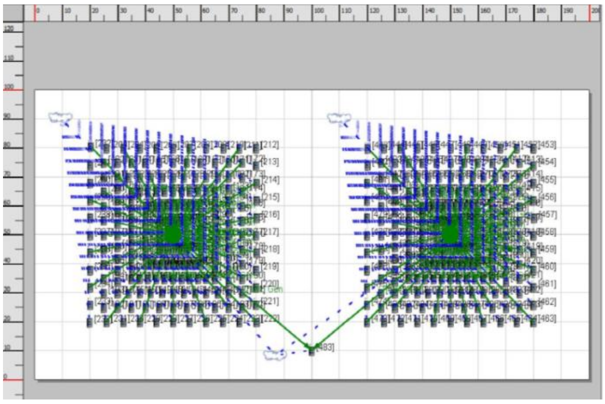

Fig. 10. The network scenario of 483 nodes in Qualnet 6.1.

Table 2. The simulation parameters.

Parameter(s)	Value(s)
Total number of nodes	242, 483
Number of PAN coordinator	1, 1
Number of RFDs	240, 480
Central node	1, 1
Communication Protocols	
RFDs to PAN coordinator	IEEE 802.15.4
PAN to Central node	IEEE 802.11
Channel frequencies (GHz)	
IEEE 802.15.4 (ZigBee)	2.4
IEEE 802.11 (Wi-Fi)	5
Packet size (bytes)	38
Packet interval (secs)	1
Simulation Time (secs)	1500
Battery (mAh)	500
Transmission range (m)	10
Nodes connectivity	Protocol, Frequency (GHz)
RFDs to PAN	ZigBee, 2.4
PAN to RFDs	ZigBee, 2.4
PAN to Central node	Wi-Fi, 5
Central node	Wi-Fi, 5
Terrain Area (m^2)	100×100, 200×100
Energy Model	Generic
Transmit circuitry Power consumption	24.75 mW
Receive circuitry power consumption	13.5 mW
Sleep circuitry power consumption	0.0051 mW
Idle circuitry power consumption	13.5 mW

5.1. Impact on network lifetime

The ability of the protocols to increase the network lifetime is compared with each other. Figure 11 illustrates that C-MAC with relay nodes has increased the network lifetime against 802.15.4 and C-MAC. The simulation results in Fig. 11 show an increase in network lifetime for the respective networks having different number of sensors. The results show that the network lifetime of both the sensor networks has become more than double. The reason is without C-MAC each node can only send data to its single parent node. The time that it has to wait for its parent to get ready to receive causes more energy consumption. It is calculated by measuring the residual battery power of all the sensor nodes in the network with a battery capacity of 500mAh excluding the residual battery power of utility provider as it has a continuous dedicated power supply. The network lifetime with C-MAC and relay nodes for both the networks of 242 and 482 sensors is the highest. Figures 12 and 13 show the variations in the values of network lifetime at different confidence intervals.

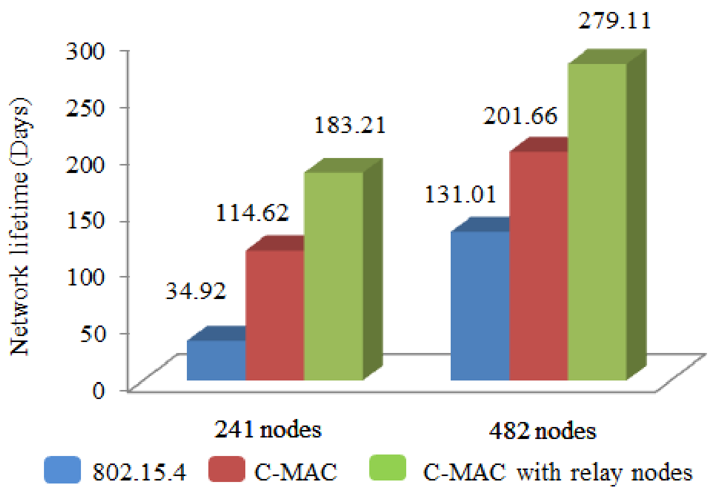

Fig. 11. The comparison of the network lifetimes of 241 and 482 nodes.

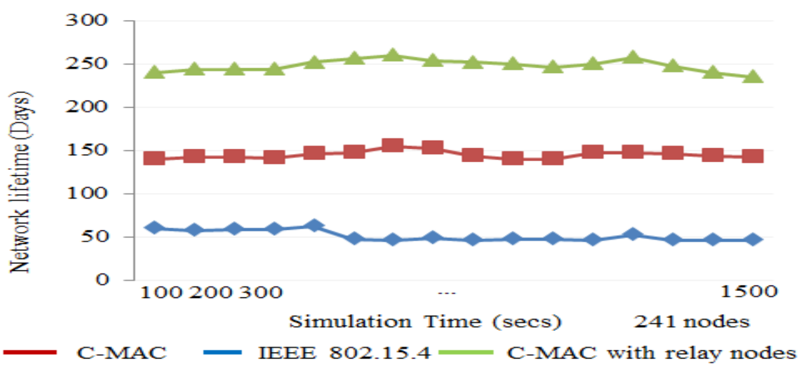

Fig. 12. The network lifetimes at different confidence intervals of 241 nodes.

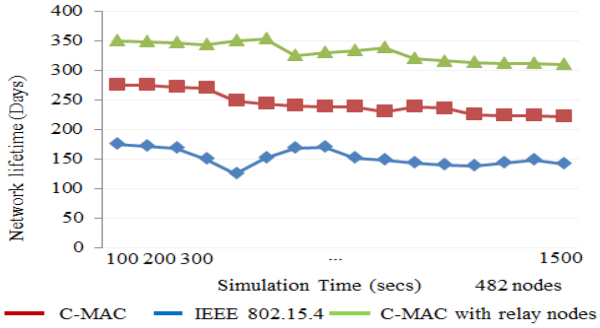

Fig. 13. The network lifetimes at different confidence intervals of 482 nodes.

5.2. Impact on throughput

Throughputs of the protocols are compared with each other in Fig. 14. The number of successful data bits received per unit time is called throughput. It is observed that the throughput increases significantly for C-MAC and C-MAC with relay nodes in comparison to 802.15.4 in both the networks. The deployment of relay nodes slightly degrades its value in the network of 241 sensors. With the increase in number of sensor nodes the presence of relay nodes with C-MAC proves to be more effective and improvise the throughput. Figures 15 and 16 demonstrate the values at regular confidence intervals from transient state to the stable state.

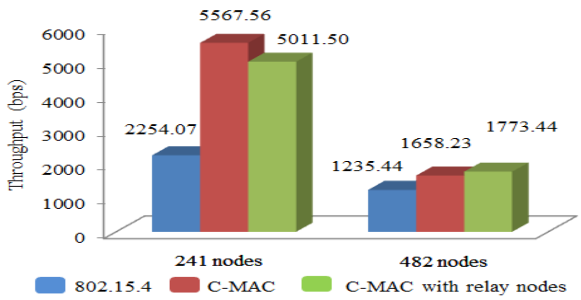

Fig. 14. The comparison of the throughputs of 241 and 482 nodes.

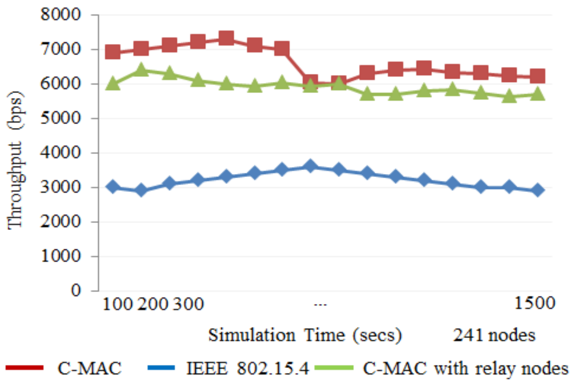

Fig. 15. The effect of C-MAC on the throughputs at different confidence intervals of 241 nodes.

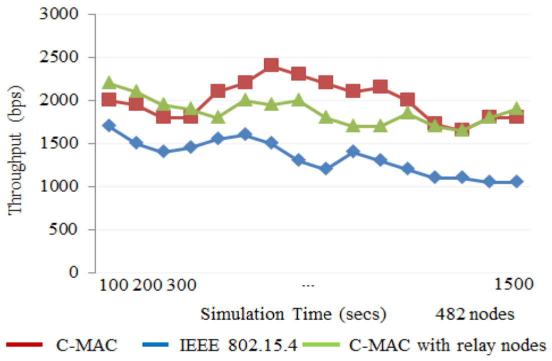

Fig. 16. The effect of C-MAC on the throughputs at different confidence intervals of 482 nodes.

5.3. Impact on average end to end delay

The effectiveness of the protocol to reduce the end to end delay is compared with each other in Fig. 17. For C-MAC and C-MAC with relay nodes it decreases for 241 nodes but for 482 nodes the values of 802.15.4 and C-MAC are comparable. In the presence of relay nodes, end to end delay increases due to channel access failure, longer transmission latency, number of hops and contention periods. The variations in its values are shown in Figures 18 and 19 with respect to the simulation time at regular confidence intervals.

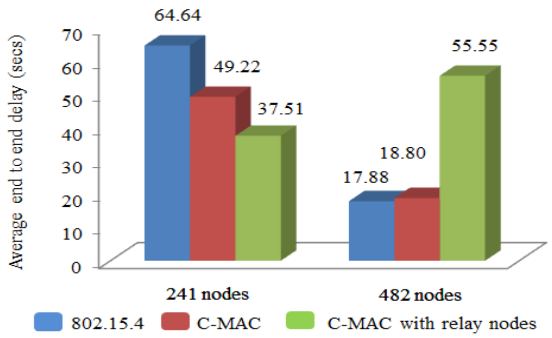

Fig. 17. The comparison of average end to end delays of 241 and 482 nodes.

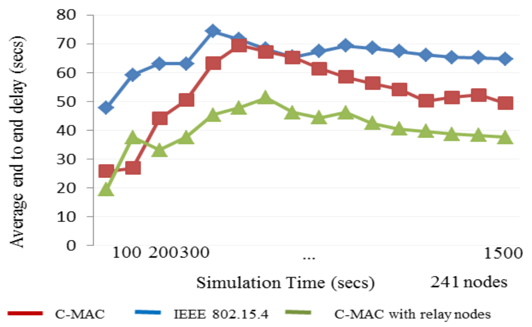

Fig. 18. The effect of C-MAC on average end to end delays of 241 nodes.

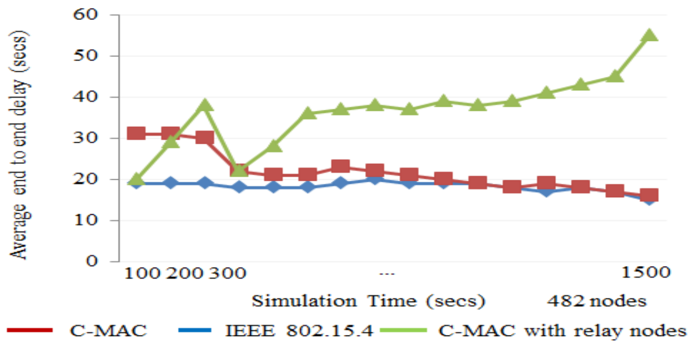

Fig. 19. The effect of C-MAC on average end to end delays of 482 nodes.

5.4. Impact on jitter

The implementation of the protocol and relay nodes has minimized the jitter. Figure 20 shows that for 241 nodes it is minimum for C-MAC with relay nodes and Fig. 21 demonstrates that for 482 nodes it is minimum for C-MAC protocol. In both the scenarios implementation of C-MAC has reduced the jitter.

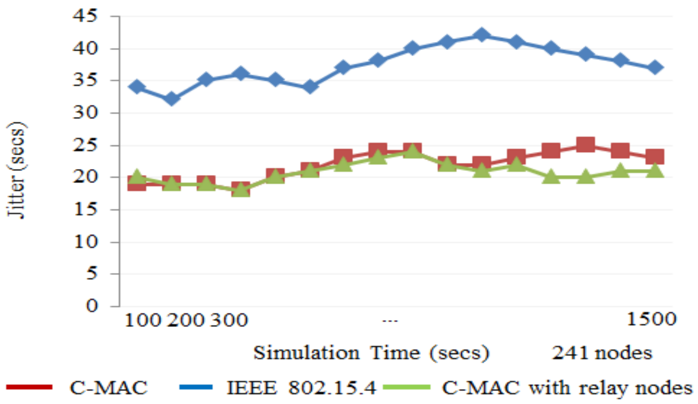

Fig. 20. The effect of C-MAC on jitter of 241 nodes.

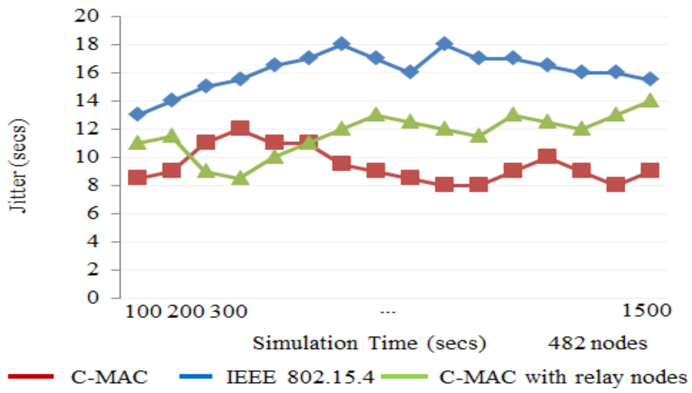

Fig. 21. The effect of C-MAC on jitter of 482 nodes.

5.5. Impact on successful data delivery ratio

The successful data delivery ratios of the protocols are compared with each other in Fig. 22. The delivery ratio is defined as the ratio of the amount of packets being correctly received at the sink to the amount being sent by all the senders. It is observed that C-MAC achieves the highest successful data delivery ratio for 241 sensors. As we proceed towards 482 sensors implementation of C-MAC with relay nodes attains the maximum value. As simulations are continued with 802.15.4 the data delivery ratio is decreased because of its higher energy consumption which causes early energy depletion of sensors. However, C-MAC has a better successful data delivery ratio and for larger sensor networks it can be further increased with the use of relay nodes.

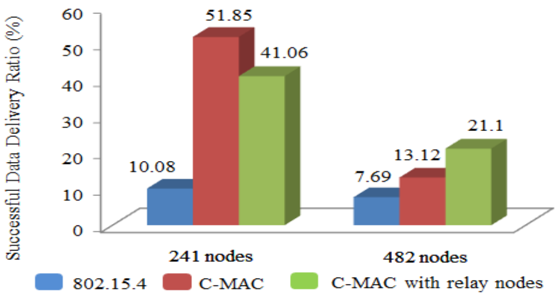

Fig. 22. The comparison of successful data delivery ratios of 241 and 482 nodes.

5.6. Impact on energy consumption

The number of alive nodes at a particular instant of time is a very vital performance metric responsible for determining the network lifetime, extent of coverage of network area and capability of multi-hop data transmissions. Figures 23 and 24 illustrate the number of alive nodes with respect to the network lifetime. The performance of the sensor networks with C-MAC and C-MAC with relay nodes surpasses the performance of the sensor network using 802.15.4 protocol. As shown in the charts, C-MAC keeps sensor nodes alive for longer duration by preventing bottlenecks in the parent nodes and the idle listening problem in children nodes as they waste energy and finally die out early.

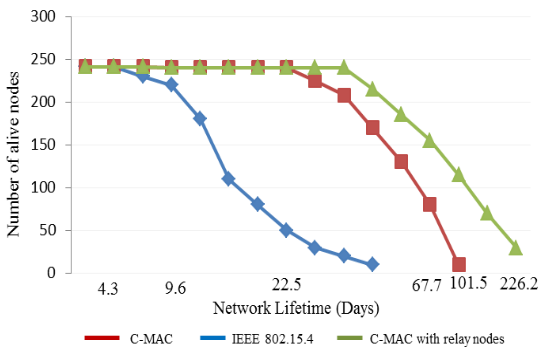

Fig. 23. The effect of different protocols on the percentage of alive nodes of 241 nodes.

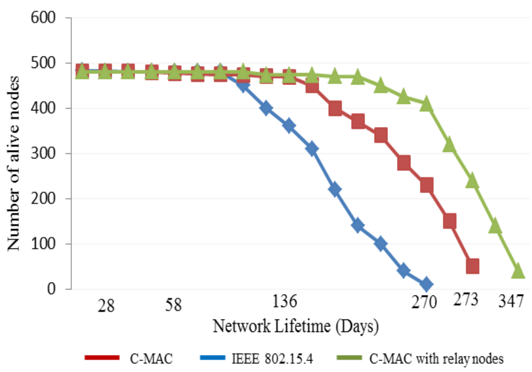

Fig. 24. The effect of different protocols on the percentage of alive nodes of 482 nodes.

6. Conclusions and Future Work

In this paper, we propose a new MAC protocol with the analysis of various parameters like throughput, average end to end delay, successful data delivery ratio and network lifetime. It reveals that the proposed C-MAC protocol with relay nodes is a promising energy-efficient protocol for energy consumption monitoring in the harsh environments of well-planned power grids. It should also be noted that the selection of grid size and radio models are crucial in large networks when the greater number of sub-networks are involved. So, we can dynamically adjust the grid size and select the most suitable radio model for different environments of the smart grid in the future.

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