Resilient IEEE802.15.4MAC Protocol for Multi-Hop Mesh Wireless Sensor Network

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Abstract—**The success of a modern power grid system is inevitably based on the integration of a smart data exchange amid several devices in power production, transportation, dispatching and loads. For large coverage data exchange, a distributed multi-hop mesh is structured from low voltage distribution boards to the substations. Thus, being cheap, less power intake, easy set-up and operating in a free licensed spectrum, ZigBee/IEEE802.15.4 makes the most suitable wireless protocol for communicating in power grid systems. Nevertheless, IEEE802.15.4MAC protocol lacks a mechanism to enable a multi-hop mesh network with efficient energy and quality of service (QoS). Hence, in this paper, a Multi-Hop Mesh IEEE802.15.4MAC protocol is designed for a large coverage data exchange. This developed model provides a resilient network with energy efficiency and QoS. Hence, the IEEE802.15.4 super_frame standard_structure is modified by swapping the contention_free period (CFP) and contention_access period (CAP) for time sensitive applications. For network resilience, a Reserved_Broadcast Duration_Slot (RB_DS) is introduced in the active super_frame standard_structure as beacon_offset reference time computation. Finally, for the network performance analysis, the developed Markov chain_Model with retry and saturated traffic regime without feedback is run on NS-2 simulator. Here, the hidden terminal problem is not considered since it is assumed that all nodes can "hear" each other. The simulation results are encouraging as the developed IEEE802.15.4MAC protocol is capable of improving the time delivery delay up to 35.7%.**

Index Terms—**Resilient; Multi-Hop Mesh; IEEE802.15.4MAC Protocol; Zigbee; Wireless Sensor Network.**

I. INTRODUCTION

The today power system has been in use for many years. Thus, several elements are close to their lifespan limit. The modern power grid system known as smart grid is a power network based on hi-tech production, transportation and dispatching of electricity to users more proficiently. In modern grid, the power dispatcher section controls and auto-adjusts the services of all devices from production to dispatching sections through power communication grid [1]. The keystone of a modern power grid is its use of full-duplex communication networks for data exchange amid its various units. The smart grid dispatcher section is made up of intelligent devices such as smart meters, Advanced Metering Infrastructure (AMI) gateways and repeaters [2]. Due to its cost-effective sensing, wireless sensor network (WSN) is one of the best communication remedies for various applications in smart grid dispatcher sections. For large coverage, sensors form a multi-hop mesh linkage to proficiently convey data for lengthy distances [3].

Being one of the best etiquettes for WSNs, ZigBee/IEEE802.15.4 is a low cost, stout, easy to set-up, low bandwidth requirement protocol and it works in the 2.4GHz unrestricted Industrial, Scientific and Medical (ISM) radio frequency range [4]. Nevertheless, for data exchange, the IEEE802.15.4MAC sub-layer provides two procedures: no-beacon asynchronous and beacon synchronous style. In fact, in the no-beacon asynchronous style, sensors remain active permanently, which may quickly drain battery power. Moreover, in this no-beacon style, there is no certainty of data conveyance. However, all transportations are completed after the accomplishment of a no slotted_carrier_sense multiple access with collision_avoidance (CSMA_CA) process. In contrast, the beacon style provides guarantee of data delivery. All transportations are completed after accomplishing a slotted CSMA_CA process. In fact, the use of synchronization mode in the beacon style permits sensors to be inactive amidst harmonized transportation, which leads to network energy proficiency [5].

In fact, the IEEE802.15.4MAC protocol restricts the no-beacon style to star topology (one_hop limited) or cluster_tree topology (less scalable and robust) [6]. Therefore, this paper designs a Multi-Hop Mesh IEEE802.15.4MAC protocol based on beacon_mode for time-sensitive applications in power grid distribution systems.

II. MODEL DESCRIPTION

IEEE802.15.4 network uses Full_Function_Device (F.F.D) and Reduced_Function_Device (R.F.D) as nodes. F.F.D or beacon_node works as Personal_Area_Network_ Coordinators (PANcs), Cluster_Head (C_H) or Routers. R.F.D or no-beacon node may simply work as front_end_devices [7].

The IEEE802.15.4 super_frame structure in Figure 1 involves a CAP in which nodes with ordinary data contest for canal entry by experiencing a slotted CSMA_CA process and a CFP which holds the Guaranteed_Time_Slot (G.T.S) for time restricted data [8].

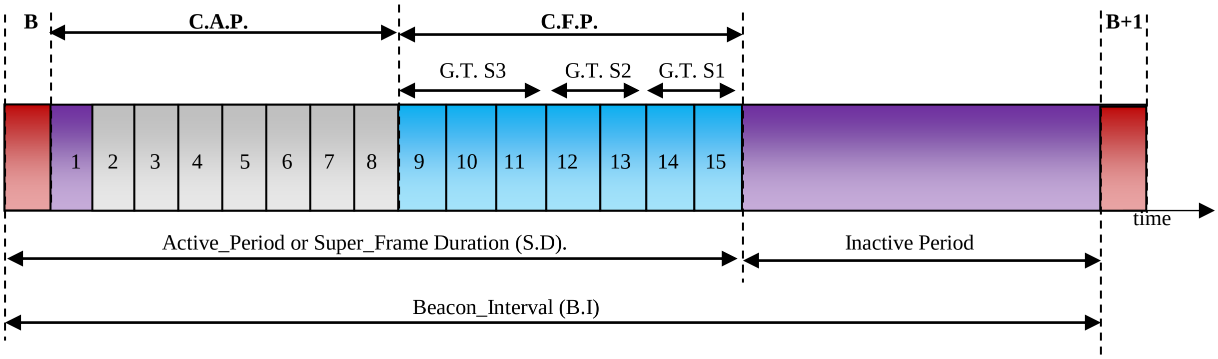

Figure 1: IEEE802.15.4std Super_Frame_Structure [13]

IEEE802.15.4_CSMA_CA algorithm utilizes three vital factors [9]: Firstly, the Back_off_Number (NB) that is the maximum waiting time for a node to attempt the canal access. NB is reset to zero before each data transmission. Second, the Window of Contention (CW) that is a counter limiting the number of slots to be empty beforehand the beginning of data broadcast. CW is reset to two before each fresh canal access attempt and increased by two every period the canal is evaluated occupied. Third, the Back_off Exponent (BE) that is correlated to the count slot periods a device might delay before starting the canal assessment [10]. While this IEEE802.15.4 CSMA_CA technique is alike the IEEE802.11 CSMA_CA in utilizing the binary exponential bac_koff, the IEEE802.15.4 mechanism contrasts that of IEEE802.11 in this: in IEEE802.15.4_CSMA_CA, a bac_koff counter value of the node drops irrespective of the canal status and it completes two clear canal assessment (CCA) once the back_off counter value attains zero [11].

III. PROBLEM DEFINITION

The modern power grid systems oblige extremely robust communication techniques for data exchange among grid devices [12]. This paper concentrates on the dispatching section where a multi-hop wireless sensor mesh network is formed for wide coverage data communication.

Despite being one of the top protocols for multi-hop wireless sensor mesh network, IEEE802.15.4 standard has the following shortcomings: Firstly, the sensed data is held by the neighbor sensor until the new beacon announcement [13]. Secondly, with the implementation of GTS, the sensed time restricted data is transmitted after the active period. Thirdly, the overall network performance is diminished by the fact that a node competes with others for canal entry in the C.A.P. Fourthly, the ordinary data has a rapid canal entry than the time restricted data as the CFP is placed after the CAP [14]. Sixthly, since for the sake of battery energy saving, it is commended to fix a wide inactive period (low duty_cycle), the sensed data is retained for a minimum period equivalent to the no active_period as per Equation (1) [15].

$$Inactive\ Period = BI - SD \tag{1}$$

Lastly, if the Duty_Cycle (D.C) as per Equation (2) [16] is fixed very small, the broadcast delay may rise as throughout the inactive period, the sensed data may have to wait until the next beacon [17].

$$DC = SD/BI = 2^{(SO-BO)} \tag{2}$$

where: BO = Beacon Order and SO = Super_Frame Order

The Beacon_Interval (B.I) and the Super_Frame_Duration (S.D) are as below:

$$B.I = aBase.Superframe.Duration \times 2^{BO} \tag{3}$$

$$S.D = aBase.Superframe.Duration \times 2^{SO} \tag{4}$$

with $0 \leq SO \leq BO \leq 14$.

IV. METHODOLOGY

This paper designs a Multi-Hop Mesh IEEE802.15.4MAC protocol from the enhanced IEEE802.15.4 superframe structure [5]. Thus, the novelty is the incorporation of a new time slot namely RBDS and the implementation of the beacon collision avoidance scheme for a multi-hop mesh network as per [18].

In fact, in multi-hop mesh networks, two key instructions, specifically, MLME_NEIGHBOUR-SCAN to get the beacons from the neighbor nodes and MLME_NLIST-REQ to ask the list of neighbors of neighbor nodes are compulsory for a node to construct a list table of its two hops neighbors. An RBDS is employed as time_reference to execute the beacon_offset [18].

The developed IEEE802.15.4 super_farme structure in Figure 2 has equal periods as the model in [5] but it presents the following adjustments:

i) A novel time slot branded RBDS is in place of Pending-Real-Time-Packets-Update (P.R.T.P.U) of [5]
ii) The RBDS is placed before the beacon. The RBDS is used to transmit critical time-sensitive data whereas the G.T.S is utilized to transfer ordinary time_sensitive data.

The newly developed IEEE802.15.4MAC protocol offers the enhancements as:

i) Nodes with critical time restriction data get a canal entry quicker than other nodes and they instantly send their data.
ii) The nodes with ordinary time-sensitive data do not contend for the canal entry in the CAP, as they send their data in the CFP located straight away after the beacon.
iii) Both, critical and ordinary time-sensitive data are sent and received within the same active period which mitigates the overall multi-hop mesh network time delivery delay.

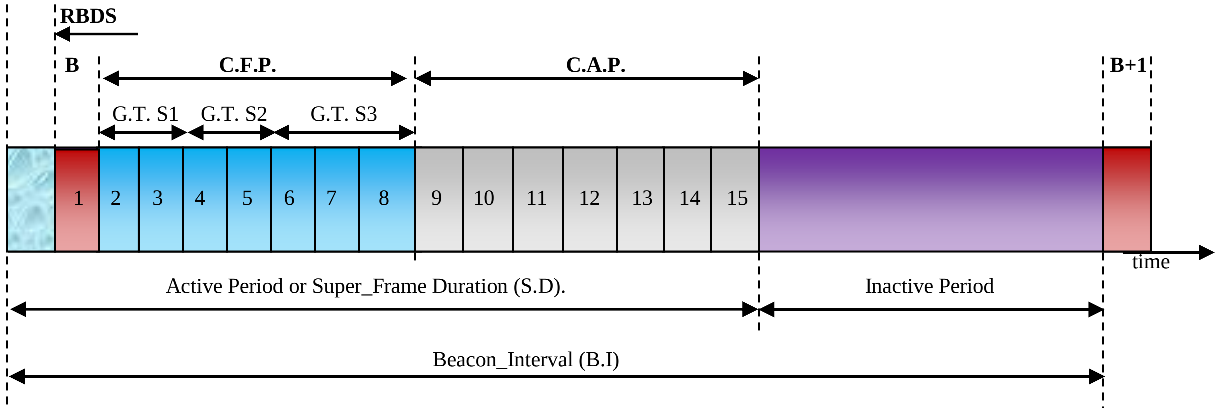

Figure 2: IEEE802.15.4 Super_Frame Structure with RBDS Model

V. MARKOV_CHAIN MODEL

Here, a queuing theory model is introduced for the developed multi-hop mesh IEEE802.15.4 MAC protocol. Hence, a retry and saturated network traffic without acknowledgment mechanism are assumed for the benefit of network power proficiency. Moreover, it is considered that all FFDs link with each other thus, leading to no existence of hidden terminal problem whilst the data is completely received. Finally, the Markov_Chain model, in Figure 3, is built on CSMA_CA slotted scheme to offer the network QoS as suggested in [19] and [20].

Assume N to be the extreme amount of similar routers (FFDs) working on a $2r$ diffusion scale of node i in an array r because nodes beyond two hop_stages do not involve in a multi-hop mesh layout crash [18].

Consider $s(t)$ to be the stochastic state of the back_off stages, if $s(t) \in \{0, \ldots, M\}$ with M the uppermost amount of Back_off_Number (NB) or the diffusion stages, if $s(t) = -2$, and $c(\mathrm{t})$ are the stochastic state for the span of backoff or diffusion time counter of a node at period t. The MAC_protocol waits for an arbitrary amount of a complete back_off periods within $[0\ to\ 2^{BE} - 1]\ units$. If the back_off_period is zero, FFD evaluates the first CCA and the states $\{s(t), c(t) = -1\}$ & $\{s(t), c(t) = -2\}$ represent the CCA_1 and CCA_2, respectively. If 2 subsequent clear-channel-assessments $(C.C.A)$ become inactive, and the FFD sends the data packets immediately. On the other hand, if anyone of $C.C.A$ stops as the medium is engaged, the value from both NB and BE is respectively added by one to $macMaxCSMABackoffs$ and $macMaxBE$. Lastly, if $NB > macMaxCSMABackoffs$, the transmission flops.

In fact, the inactive status $\{\mathrm{s(t)} = -1, \mathrm{c(t)} = 0\}$ denotes the inactive state if there is no prominent data for broadcasting. Hence, it is assumed that there is always data to send to send. Last, the state $\{\mathrm{s(t)} = -2, \mathrm{c(t)} = 0, \ldots, \mathrm{L} - 1\}$ characterizes the transmission state where L is the data delivery period in slits. The arbitrarily chosen back_off_window magnitude at step i may be in the range of $\{0, \mathrm{W_i} - 1\}$ with zero value designates instant detection and the window_delay $(\mathrm{W_i})$ is originally fixed as $\mathrm{W_0} = 2^{\mathrm{aMinBE}}$ and multiplied by two at each step until $\mathrm{W_i} = \mathrm{W_{max}} = 2^{\mathrm{aMaxBE}}$ where $(\mathrm{aMaxBE} - \mathrm{aMinBE}) \leq \mathrm{i} \leq \mathrm{NB}$ [21].

Let α be the possibility of evaluating the canal occupied under CCA_1 whereas β be the possibility of evaluating it engaged thru CCA_2, taking it was inactive in CCA_1. Figure 3 demonstrates the 2*D_Markov_chain Design for multi-hop mesh layout based on CSMA_CA mechanism with status represented by $\{s(t), c(t)\}$ at a stipulated time t.

Finally, in the present model, $\delta = 1/N$ is the likelihood of an unavailability of network canal entry [18].

In fact, by inspecting the above Figure 3, the shift probabilities are obtained as:

$$p\{i,k|_{i,k+1}\} = 1, i \in (0,M), k \in (0, W_i - 2) \tag{5}$$

$$p\{0,k|_{i,0}\} = [(1-\alpha)(1-\beta)(1-\delta) + \delta]/W_0, \tag{6}$$

with $i \in (0, M-1), k \in (0, W_0 - 1)$

$$p\{i,k|_{i-1,0}\} = \{(1-\delta)[\alpha + \beta - \alpha\beta] + \delta\}/W_i, \tag{7}$$

with $i \in (1, M), k \in (0, W_i - 1)$

$$p\{0,k|_{M,0}\} = 1/W_0,\ k \in (0, W_o - 1) \tag{8}$$

If the stationary possibility of being in the status $\{i,k\}$ is:

$$b_{-1,0} = \lim_{t\to\infty} P\{(s(t), c(t)) = (-1,0)\} \tag{9}$$

and

$$b_{-2,k} = \lim_{t\to\infty} P\{(s(t), c(t)) = (-2,k)\} \tag{10}$$

Therefore:

$$b_{i,-1} = (1-\delta)b_{i,0} \tag{11}$$

$$b_{i,0} = \alpha \times b_{i-1,-1} + \beta \times b_{i-1,-2} + \delta \times b_{i-1,0} \tag{12}$$

$$b_{i-1,-1} = (1-\delta)b_{i-1,0} \tag{13}$$

$$b_{i-1,-2} = (1-\alpha)(1-\delta)b_{i-1,0} \tag{14}$$

Then substituting the Equation (13) & (14) into (13), yields to:

$$\begin{aligned} b_{i,o} &= [\alpha(1-\delta) + \beta(1-\alpha)(1-\delta+\delta)]b_{i-1,0} \\ &= [(1-\delta)(\alpha+\beta-\alpha\beta)+\delta]b_{i-1,0} \end{aligned} \tag{15}$$

The generalized formulation can be defined as:

$$\begin{cases} b_{i,0} = p^i b_{0,0} \\ b_{i,-1} = (1-\delta)p^i b_{0,0} \end{cases} \quad for\ i \in (0,M) \tag{16}$$

where $p = [(1-\delta)(\alpha+\beta-\alpha\beta)+\delta]$

Based on the Markov_chain regularities, the next relations below are achieved:

$$b_{i,k}=\frac{(W_i-k)}{W_i}\times b_{i,o}, i\in(0,M), k\in(1,W_i-1) \qquad (17)$$

$$\sum_{k=0}^{L-1}b_{-2,k}=L(1-\alpha)(1-\beta)(1-\delta)\sum_{i=0}^{M}b_{i,o} \qquad (18)$$

As the total probabilities should be 1, the Equation (19) is obtained as follow:

$$1=\sum_{i=0}^{M}\sum_{k=0}^{W_i-1}b_{i,k}+\sum_{i=0}^{M}b_{i,-1}+\sum_{i=0}^{M}b_{i,-2}+\sum_{k=0}^{L-1}b_{-2,k}=\sum_{i=0}^{M}b_{i,0}\left\{\frac{W_i-1}{2}+(1-\delta)\big[1+(1-\alpha)[1+(1-\delta)L]\big]\right\} \qquad (19)$$

Replacing the expression of W_i into Equation (19) produces to the following Equation (20):

$$1=\left(\frac{b_{0,0}}{2}\right)\times\left\{-1+2(1-\delta)\big[1+(1-\alpha)[1+(1-\beta)L]\big]\times\left[\frac{1-P^{M+1}}{1-p}\right]+2^dW_0\left[\frac{p^{d+1}-P^{M}}{1-p}\right]+W_0\left[\frac{1-2p^{d+1}}{1-2p}\right]\right\} \qquad (20)$$

where $\mathrm{d}=\mathrm{aMaxBE}-\mathrm{aMinBE}$.

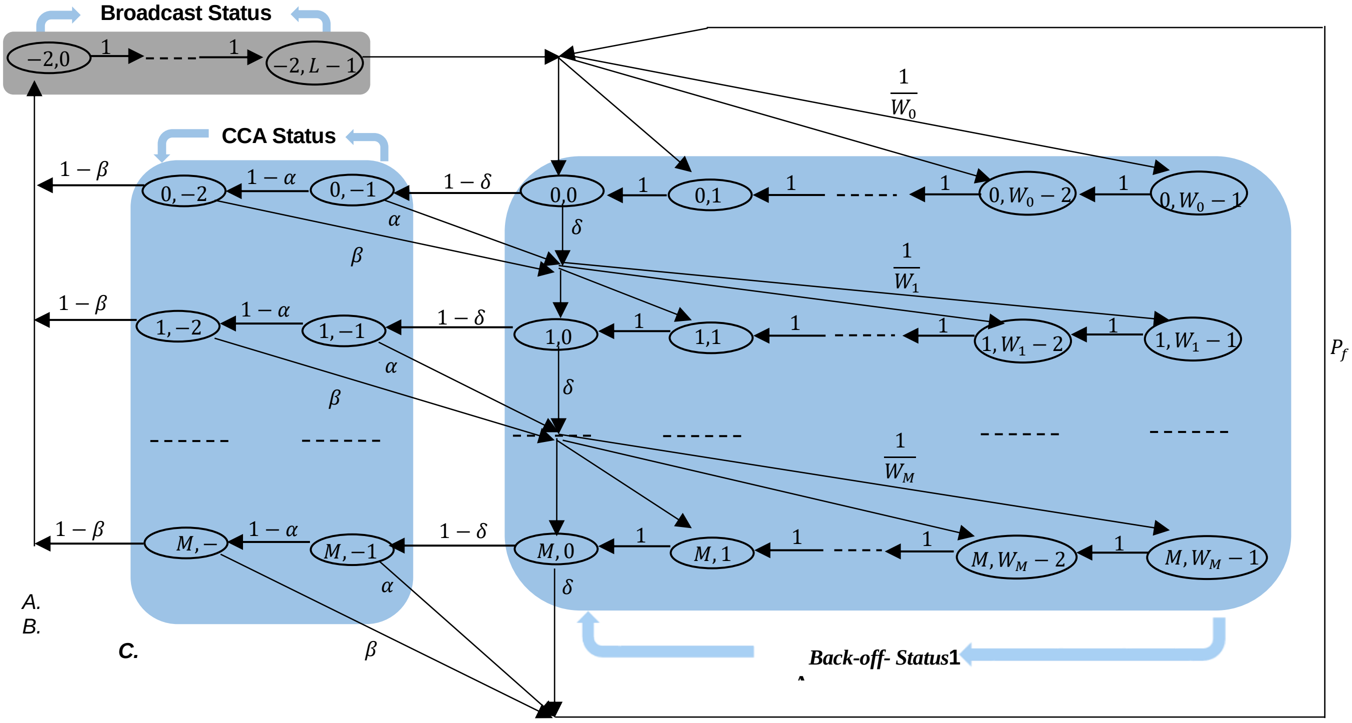

Figure 3: 2*D Markov_Chain Model for Multi-Hop Mesh IEEE802.15.4MAC Protocol Based CSMA_CA Mechanism

The possibility that a node initiates the broadcast is equal to the broadcast probability τ in Bianchi's model [17] and it is adapted for this design as follow:

$$\tau=P_S=\emptyset(1-\alpha)(1-\beta)(1-\delta)=\emptyset Z \qquad (21)$$

in which the stationary possibility $\emptyset=\sum_{i=0}^{M}b_{i,o}$

By considering the communication among nodes as per [16], the values for α, β and $\emptyset$ are found as:

$$\alpha=L\left[1-\big(1-\emptyset(1-\delta)\big)^{\delta(N-1)}\right](1-\alpha)(1-\beta) \qquad (22)$$

$$\beta=\left[1-\frac{1}{1+\frac{1}{1-\big(1-\emptyset(1-\delta)\big)^{\delta N}}}\right]\Big[1-\big(1-\emptyset(1-\delta)\big)^{\delta(N-1)}\Big] \qquad (23)$$

$$\emptyset=\sum_{i=0}^{M}b_{i,0}=\frac{1-P^{M+1}}{1-p}b_{0,0} \qquad (24)$$

It is well known that the stationary possibility, $\emptyset$ for a sensor to try a $C.C.A$ for the foremost period inside a slot, is persistent and self-regulating throughout the interacted nodes [16].

VI. RESULT SIMULATION AND DISCUSSIONS

The proposed IEEE802.15.4MAC model for Multi-Hop Mesh WSN is validated by comparing its simulation results with IEEE802.15.4MAC Standard results using NS-2 simulator [20]. To endorse the Markov_Chain model, the mathematical results are compared with the simulation results for network throughput and power consumption. The simulation parameters used for this model are summarized in the Tables 1 and 2 below.

Table 1

General Network Parameters

General Parameters		Chipcon's CC2521 Radio Parameters	
Amount of FFD	0, 21, 30, 40, 50, 61	Data Rate	260Kbps
Lay out	Multi-Hop Mesh	Frequency Band	2.4GHz
Size of Packet	50 bytes	Energy Consumed in R_X stage (P_{rx})	35.46mW
Duration of	2100 seconds	Energy Consumed in T_X stage (P_{tx})	31.32mW
Simulation	15m	CCA	30mW
Communication Span	1 packet each B.I	Idle	0.8mW
Communication Rate	None	Sleep	0.16mW
Routing_protocol	Disabled		
A.R.P	> 112		
Number-of-scenarios	Reserved		
0 × 0a-0			

Table 2
Setting Parameters

Variable and fix parameters		Packets	
macMaxCSMABackoff	0~5, default 4	MAC_{Header}	2 slots
aMinBE	0~3, default 3	$Data_{Payload}$	12 slots
aMaxBE	5	L	$MAC_{Header} + Data_{Payload}$
CW	2		
1 slot	0.32 ms		
aUnitBackoffPeriod	80 bit/slot		

A. Multi-Hop Mesh IEEE802.15.4MAC Protocol Analysis

To authenticate the Multi-Hop Mesh IEEE802.15.4MAC Protocol, its delivery time delay and reliability simulation results are compared with those of IEEE802.15.4 MAC Standard.

In fact, the graph in Figure 4 exhibits a time delivery delay for various amounts of network nodes. Hence, as predicted, this developed IEEE802.15.4MAC protocol delivers improved outcomes than the IEEE802.15.4standard for various network sizes. This is due to the use of the RBDS slot as well as the swapping of CAP with the CFP in the IEEE802.15.4MAC Sub_layer super_frame.

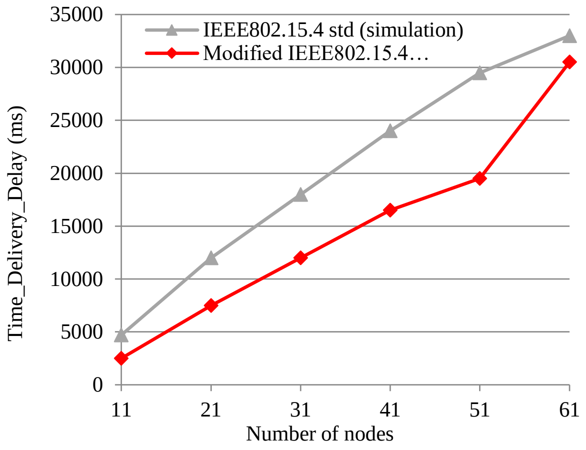

Figure 4: Time_Delivery_Delay against Network Size

From Figure 5 below, the developed IEEE802.15.4MAC protocol produces better-quality results compared to the IEEE802.15.4standard in term of system reliability. In fact, this is the result of the decrease of pointless back_off time among data packets in the IEEE802.15.4.

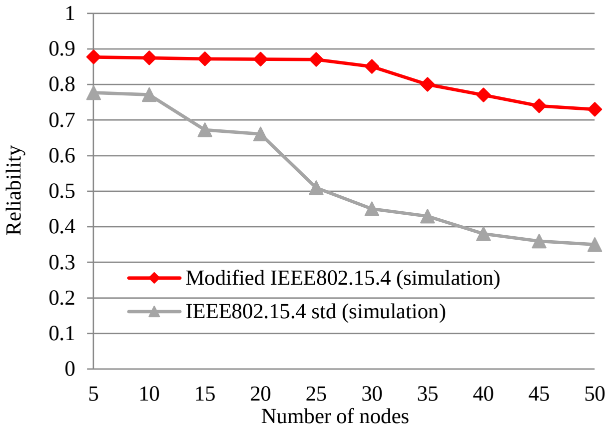

Figure 5: Reliability against Network Size

B. Markov Model Validation

The mathematical results are compared with the simulation results to confirm the Markov_chain_Model.

C. Throughput Analysis

Considering the impact of DC, the network throughput is obtained as per the following Equation (25).

$$S = LN\emptyset(1-\delta)[1-\emptyset(1-\delta)]^{\delta(N-1)}(1-\alpha)(1-\beta)2^{(SO-BO)} \tag{25}$$

Thus, the Figure 6 confirms the Markov_chain_Model derived for a Multi-Hop Mesh IEEE802.15.4MAC protocol despite the slight mismatch (due to manual calculations) between the simulations results and mathematical results for the throughput analysis.

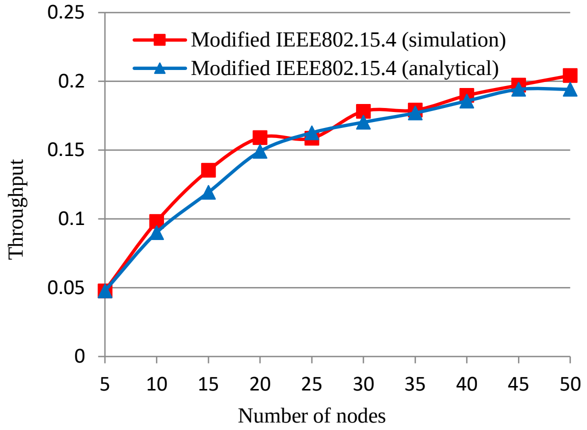

Figure 6: Throughput against Network Size

D. Power Consumption Evaluation

In power intake study, the components like slits engaged for intermittent beacon broadcast and reception (T_{bcn}), the CAP and sleep-to-inactive changeover time (T_{si}) are involved. Therefore, the average nodal energy intake is quantified as follow:

$$E_{av} = \frac{T_{bcn}}{BI} P_{rx} + \frac{SD}{BI}[L(1-\alpha)(1-\beta)(1-\gamma)P_{tx} + (1-\gamma)(2-\alpha)P_{rx}] \quad (26)$$

Therefore, the simulations result and mathematical calculations for power intake against network size are compared in Figure 7.

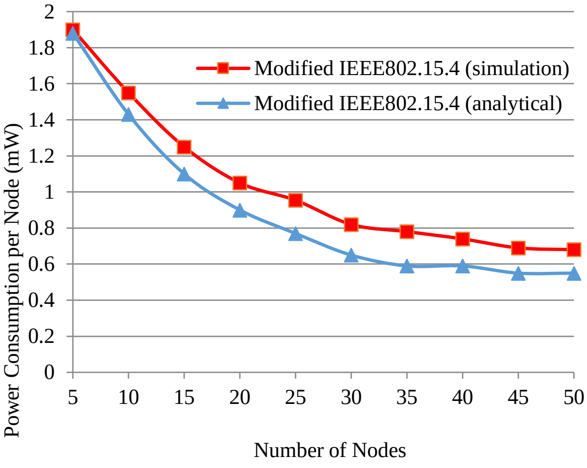

Figure 7: Power Consumption against Network Size

As it is seen in the above Figure 7, the network power consumption diminishes with the rise of the number of nodes. That is one of multi-hop mesh network advantages. Again, the Markov_chain_Model of the developed IEEE802.15.4MAC model is approved despite minor difference (due to manual calculations) between the simulations results and mathematical results for network power consumption per nodes.

VII. CONCLUSION

This paper designs a Multi-Hop Mesh IEEE802.15.4MAC protocol on beacon style with CSMA_CA mechanism for real-time applications of smart grid distribution systems. The IEEE802.15.4 super_frame standard was modified by swapping the contention_free_period $(C.F.P)$ and contention_access period $(C.A.P)$ for time restricted applications. For network resilience and quality of service (QoS), a time reference named Reserved_Broadcast_Duration_Slot (RBDS) was used in the active super_frame structure for beacon_offset execution. Moreover, for the network performance analysis, the developed Markov_chain_Model admitting retry and saturated traffic state with no feedback technique was run on NS-2 simulator. The validation of the mathematical model has been proven as its calculations thoroughly match the simulation results. Finally, the obtained outcomes are motivating as the proposed Multi-Hop Mesh IEEE802.15.4 MAC protocol can improve the time delivery delay up to 35.7%. As it is crucial to test the proposed model in real-world environment, in the future works, this model will be implemented on real-sensors using the iLive platform [22] with the Atmel open MAC stack protocol since it provides an open source implementation of the IEEE 802.15.4 standard [23].

ACKNOWLEDGMENT

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