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Evaluation of Slotted CSMA/CA of IEEE 802.15.4

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***Abstract*—IEEE 802.15.4 standard is specifically designed for low Rate Wireless Personal Area Network (LR-WPAN) with low data rate and low power capabilities. Due to very low power consumption with duty cycle even less than 0.1, the standard is being widely applied in Wireless Sensor Networks applications. It operates in Beacon and Non Beacon enabled modes. During Beacon enabled mode, it has Contention Access Period (CAP) and optional Contention Free Period. We have analyzed its performance during CAP where slotted CSMA/CA algorithm is used. The performance analysis includes channel access busy, transmission failure chances along with reliability and throughput against all three frequency bands with load variation.**

I. INTRODUCTION

Since last decade, wireless technologies are emerging rapidly due to increase in wireless application demand. In order to meet these application requirements, several protocols were also introduced like IEEE 802.11, IEEE 802.16 and IEEE 802.15.4. For higher data rates wireless applications, IEEE802.11 and IEEE802.16 are used. IEEE802.15.4 standard [1] is specifically designed for those applications where low data rate with higher reliability and less power consumption is required. The applications like continuous monitoring of atmospheric conditions deploy wireless sensors having less processing capabilities. As these wireless sensors having limited inbuilt battery with less processing needs which requires a protocol like IEEE 802.15.4. The standard is suitable for fixed as well as portable wireless sensors with the aim to provide low power, low cost and high reliability [2][3][4] . It offers three different frequency ranges off which 2.4GHz frequency band is free throughout the world and hence is largely used throughout the world. In this paper, we have contributed by analyzing the performance measures of IEEE 802.15.4 in three different frequency bands. This comprehensive analysis is done in the same environment with fixed number of nodes and the same load variation when they are operating at different frequency bands.

The remainder of this paper is organized as related work describing the performance studies done by other authors in this field. An overview of the standard along with the calculation of its different parameters is discussed in section III. Section IV describes slotted CSMA/CA algorithm and results and analysis are shown in section V whereas conclusion is in VI.

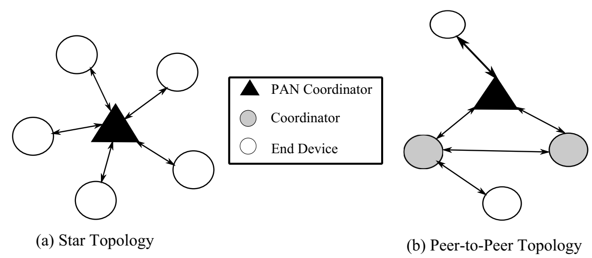

Fig. 1. *Star and peer-to-peer topology.*

II. RELATED WORK

IEEE 802.15.4 standard got attraction due to its low duty cycle and less energy consumption. Due to these lucrative features, many authors have evaluated its performance in different scenarios. Several authors [5][6] analyzed the unslotted CSMA/CA performance in different prospects. There are also number of simulation based studies [7][8][9] in order to analyze the standard's performance in different prospects. Pollin in [10] analyzed its performance by using the Markov chain model with saturated load whereas in [11] Jung has done a throughput analysis on slotted CSMA/CA by using enhanced Markov Chain model during unsaturated region. However, no one has analyzed slotted CSMA/CA performance on all of its frequency bands. We have analyzed the performance of slotted CSMA/CA on its different frequency channels calculated the probability by following the General Markov channel model described in [12].

III. OVERVIEW OF IEEE 802.15.4 STANDARD

IEEE 802.15.4 standard is designed for Low Rate Wireless Personal Area Network (LR-WPAN). It operates at both Physical and MAC layer with duty cycle of less than 0.1. In LR-WPAN, two types of wireless nodes called as Fully Functional Device (FFD) and Reduced Functional Device (RFD). FFD may be a PAN Coordinator, a Coordinator or a simple node whereas RFD can only act as simple wireless node. FFD has capability to exchange its information both with FFD and RFD whereas RFD can not exchange its information with other RFD that's why RFD only placed as end node of any wireless network. LR-WPAN operates in star as well as in peer-to-peer fashion. Nodes associated with coordinator can communicate with coordinator in star pattern where as two or more coordinators exchange

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TABLE I
FREQUENCY BANDS WITH DATA RATE

Frequency Band (MHz)	Modulation Scheme	Symbols / sec	Bits/ symbol	Symbol Duration (sec)	bits/sec	channels supported
868 - 868.6	BPSK	20000	1	50*e-6	20000	1
902 - 928	BPSK	40000	1	25*e-6	40000	10
2400 - 2483.5	O-QPSK	62500	4	16*e-6	250000	16

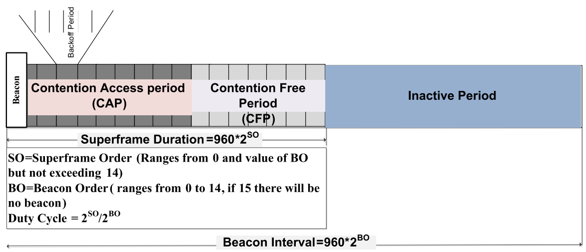

Fig. 2. *Superframe Structure with CAP and CFP.*

their information by following peer-to-peer topology. Fig.1 shows nodes communicating in Star as well as in Peer-to-Peer.

The standard operates in three different frequency bands as 868MHz,915MHz and 2.4GHz by offering data rates of 20Kbps, 40Kbps and 250Kbps respectively. These frequency bands uses 27 frequency channels from 0 to 26 as channel 0 at 868MHz, 1-10 at 915MHz and 11-26 at 2.4GHz frequency bands. Different frequency bands with respective data rates are shown in table 1.

IEEE 802.15.4 supports beacon enabled and non-beacon enabled modes. The later uses un-slotted CSMA/CA algorithm and earlier applies Superframe structure and consists of two parts called active period and inactive period. Active period consists of beacon frame followed by the Contention Access Period (CAP) and optional Contention Free Period (CFP) as shown in fig.2. Slotted CSMA/CA algorithm is used during CAP of beacon enabled mode.
Coordinator disseminates beacon frame on the network after regular intervals and all the associated nodes listen to it to follow these instructions. Beacon frame is also used to synchronize all the associated nodes so that all nodes must awake up just before start of next beacon from coordinator. All requests along with some data packets from nodes to coordinator are transferred during CAP. Information relating to Length of active superframe duration, next Beacon arrival time and Slot duration for each slot can be attained from the superframe specs field of the beacon frame as shown in figure 4 and can be determined from equations 8, 9 and 10 respectively.

A. Calculations from superframe

Information about Beacon Intervals (BI) and Superframe Duration (SD) depends upon a constant value of aBaseSuperFrameDuration (BSFD) as well as the values of Beacon Order (BO) and Superframe Order (SO) as mentioned in superframe specs shown in figure 4. Whereas BSFD depends upon the fixed values of aNumSuperframeSlot (NSS) and aBaseSlotDuration (BSD). BI and SD can be calculated as follows.

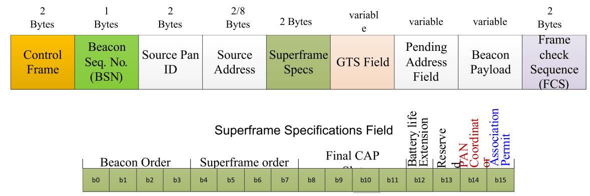

Fig. 3. *Beacon frame with Superframe specs field description.*

$$BI = BSFD \times 2^{BO}(Symbols) \quad (1)$$

Where value of BO ranges from 0 to 14
And

$$SD = BSFD \times 2^{SO}(Symbols) \quad (2)$$

Here value of SO ranges from 0 to BO
Where as BSFD is calculated as

$$BSFD = NSS \times BSD(Symbols) \quad (3)$$

$NSS = 16(default)$
$NSS = 16\ (IEEE\ 802.15.4\ standard)$

$$BSD = 3 \times aUnitBackoffPeriod \quad (4)$$

aUnitBackoffPeriod=20(Symbols)

$$BSD = 60(Symbols) \quad (5)$$

$$BSFD = 960(Symbols) \quad (6)$$

$$SD = 960 \times 2^{SO}(Symbols) \quad (7)$$

$$BI = 960 \times 2^{BO}(Symbols) \quad (8)$$

As in SD there are 16 slots so each slot duration (SlD) is calculated as

$$SlD = \frac{960 \times (2^{SO})}{16}(Symbols) \quad (9)$$

If Number of Backoff Period against one slot is mentioned by BPS
then these are calculated as

$$BPS = \frac{960 \times (2^{SO})}{16}/(20) \quad (10)$$

$Total\ BackoffPeriodsinSD$ = BPS*16
$bits/slotin868MHz$ = 960*(2^{SO})/16
$bits/slot\ in\ 915MHz$= 960 $*$ (2^{SO})/16
$bits/slot\ in\ 2.4GHz$ = 4* 960 * (2^{SO})/16
From equations 3 and 4 one can analyzed that number of Backoff Period and slot Duration depends directly on the value of Superframe Order as increases with the increase in Superframe order.

IV. Slotted CSMA/CA Mechanism

During CAP, all nodes contend to access the medium by following CSMA/CA mechanism. This algorithm depends mainly on three parameters as number of Backoff (NB), Backoff Exponent (BE) and Contention Window (CW). Initial values of NB,BE and CW are 0,3 and 2 respectively. When medium is found busy, value of NB is incremented by 1 unless it reaches its maximum limit of 4 as defined in MaxCSMABackoffs. The channel access is reported failure to the upper layer when NB exceeds its value as of MaxCSMABackoffs.

BE parameter defines the range of Backoff slots that is how manyBackoff Slots node has to wait before going to assess the channel availability. The random number of backoff period ranges from 0 to $2^{BE} - 1$. Value of BE increments when the medium access was found busy uptill amacMaxBE value of 5. This increases the random backoff duration from 0-7 to 0-31. CW parameter relates to Clear Channel Assessment (CCA) and its default value is 2 which means node will have to ensure two consecutive idle channels before transmitting frame to medium. The channel sensing is done during first 8 symbols of backoff period.

Flow diagram of CSMA/CA shows that when nodes need to transmit some frames, it first bring into line with the start of backoff boundary and then waits for the random backoff period slots. At the end of the backoff period, node senses the channel by performing CCA at boundary of its backoff period. If accessed channel is found busy, CCA value is reinitiated to its default value and values of NB and BE are incremented by 1 unless they reach their maximum limits. As maximum number of BE is 5 which means each time when channel is found busy, the random backoff value increases. Maximum range of backoff duration is from 0 to 620 Symbols.

Maximum number of backoff limit is 4. By exceeding this limit, algorithm reports a channel access failure. In case, channel is sensed idle after backoff countdown, the value of CW is decremented by 1. If its value approaches to 0 then packets are transmitted at next backoff slot boundary as shown in fig.4. This results in two consecutive channel access idle. The backoff period countdown halts if superframe duration ends up and resumes at start of the next superframe.

After successfully contending the channel access idle, the node computes whether its transmitting frame with data acknowledgment and interframe spacing can be completed within remaining superframe duration. If remaining superframe duration is larger than the computed frame transmitted time then the frame is transmitted otherwise node has to wait for start of the next superframe in order to transmit its data. Total time required to send data can be calculated as shown in fig.5.

Total Delay(TD) required to transmit data with acknowledgement

TD=$T_{backoff}$ + T_{data} + $2T_{prop}$ + T_{ta} + T_{ack} + T_{ifs}

$T_{backoff}$= $node'swaitingtimeduringBackoff$

T_{data} = $Timerequiredtotransmitframe$

T_{prop} = $propagationdelay$

T_{ta} = $TurnaroundTime$

T_{ack} = $Acknowledgementtime$

T_{ifs} = $Time\ for\ interframespace$

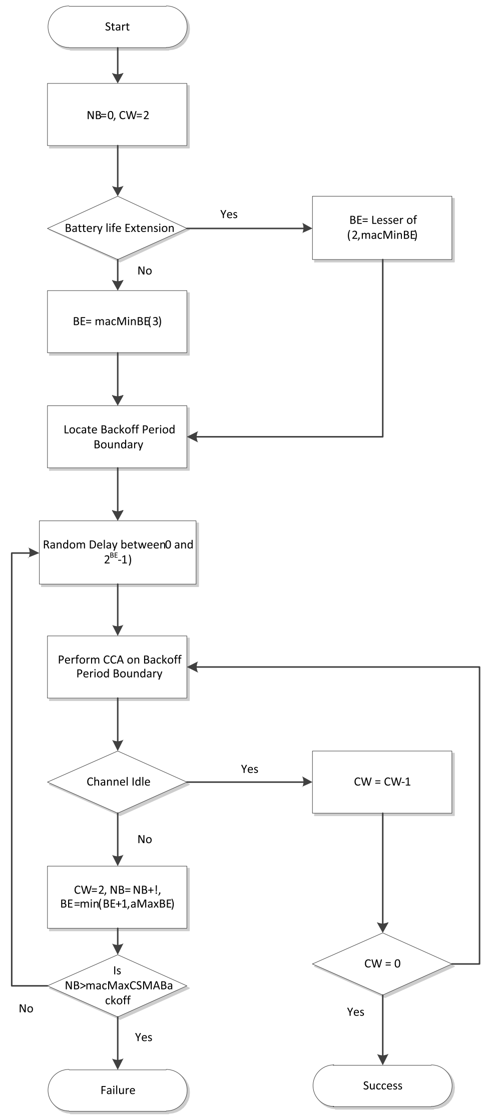

Fig. 4. *Flow diagram of Slotted CSMA/CA.*

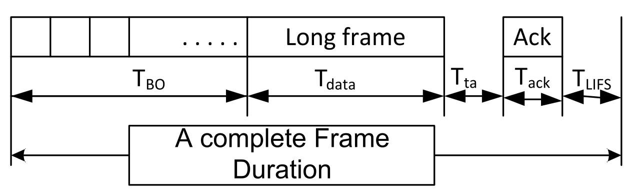

Fig. 5. *Complete frame length including Acknowledgement and Inter frame Space.*

Parameters	868MHz	915MHz	2.4GHz
Number of Nodes	10	10	10
Data Rate	20Kbps	40Kbps	250Kbps
Bits/Backoff Slot	20	20	80
Offered Load	484 to 6776 bits	484 to 6776 bits	484 to 6776 bits
aunitBackoffPeriod	20*50*e-6	20*25*e-6	20*16*e-6
Turnaround time	12*50*e-6	12*25*e-6	12*16*e-6
macAckWaitDuration	120*50*e-6	120*25*e-6	120*16*e-6
Sensing Time	8*50*e-6	8*25*e-6	8*16*e-6
LIFS	40*50*e-6	40*25*e-6	40*16*e-6
SIFS	12*50*e-6	12*25*e-6	12*16*e-6
macMinBE	3	3	3
macMaxBE	5	5	5
MaxCSMABackoff	4	4	4
macMaxFrame retries	3	3	3

TABLE II
INPUT PARAMETER VALUES

Delay required to transmit data without acknowledgement
TD=$T_{data} + T_{prop} + T_{ifs}$

V. ANALYSIS WITH RESULTS

Our analysis includes CSMA/CA performance when it is being operated under different frequency channels. The comparison includes reliability, propagability of channel access failure, throughput analysis and transmission failure probability.it also includes average wait time of the node before transmitting frame along with probability of sensing the channels access busy during CCA1 and CCA2 operation. Behavior is analyzed by increasing load on different frequency bands by keeping the parameters values as default. MATLAB simulation tool is used in order to find out the results. Probabilities are calculated by following the General Markov chain model as described by Park in [12].
Input parameter values set during these analysis are shown in table II.

A. *Probability of Assessing Channel Busy During CCA1*

After waiting for a random backoff period, the nodes sende the carrier whether it is busy or idle. The probability is calculated by following the general Markov Chain model described in as

$$\alpha = [L(1-(1-\tau)^{N-1})(1-\alpha)(1-\beta)]+$$
$$L_{ack}\frac{N_T(1-\tau)^{N-1}(1-(1-\tau)^{N-1})(1-\alpha)(1-\beta)}{1-(1-\tau)^N} \quad (11)$$

$$\alpha = (1-\alpha)(1-\beta)(1-(1-\tau)^{N-1})$$
$$[L + \frac{L_a ck(N_T(1-\tau)^{N-1})}{1} - (1-\tau)^N] \quad (12)$$

Here
α=probability of busy channel during CCA1
L=Length of data frame in slots
L_{ack}= Length of Acknowledgement frame
τ= Node attempting to sense carrier during CCA1
The results in fig 6 show that the probability of busy channel

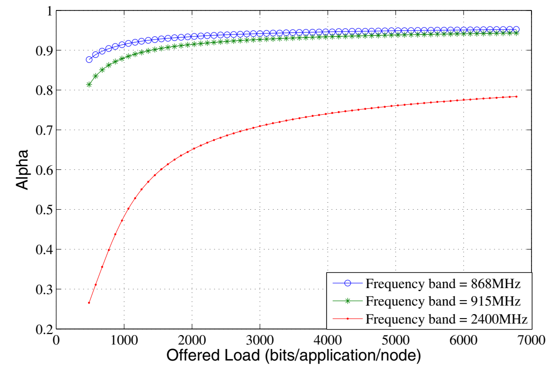

Fig. 6. *Busy channel Probability during CCA1*

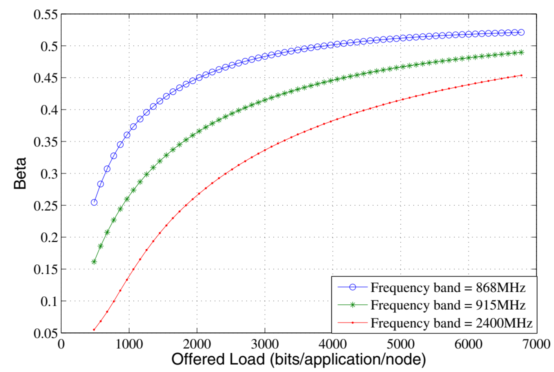

Fig. 7. *Busy channel Probability during CCA2*

is higher with the increase in load as channel will be busy for most of the time. It can be analyzed from the results shown in fig.7 that probability of channel busy during CCA1 is higher for those nodes which are operating at lower frequency bands. The channel busy probability is highest against 868MHZ channel as transmit, then the probability of 915 Mhz and the lowest probability of assessing busy channel is when nodes are operating at 2.4GHz frequency band at the same load and same number of nodes. This is due to the fact that same load requires more time to keep the channel busy where data rate is lower.

B. *Probability of Assessing Channel Busy During CCA2*

After successfully sensing the channel idle, the node senses the channel for the second time again as described in section III. The probability of sensing CCA2 is calculated as under.

$$\beta = \frac{1-(1-\tau)^{N-1} + N\tau(1-\tau)^{N-1}}{2-(1-\tau)^N + N\tau(1-\tau)^{N-1}} \quad (13)$$

Here β is Probability of busy channel during CCA2
And $[1-(1-\tau)^{N-1}]$ is a Probability of Collision when any node from rest of N-1 nodes transmit in the same time slot.
The results in fig. 7 show that finding medium idle are less

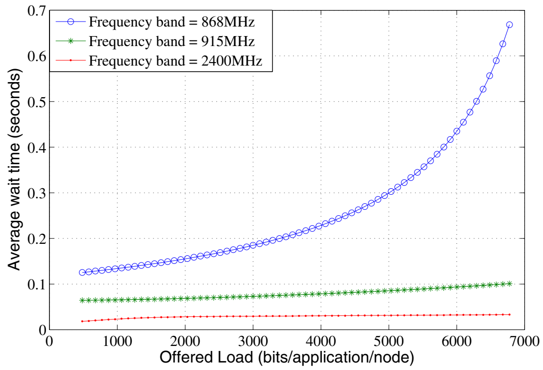

Fig. 8. *average wait time of node before transmitting frame*

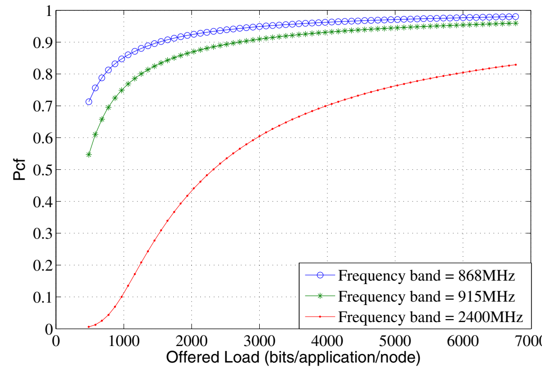

Fig. 9. *Channel access Failure Probability*

during CCA2 as compared to CCA1. This is due to the fact that during CCA2 node need not to wait for backoff slots and sensing of medium is done in the next slot. Again the effect of higher data rate can easily be compared which has the same influence as during CCA1 analysis.

C. Average Wait time before transmitting

Average wait time for holding the packet is calculated as the time which node holds the packet due to busy medium. It has been noted that waiting time is less where data rate is high as unit backoff slot is smallest in 2.4GHz frequency band, unit backoff slot duration is more against 915MHz frequency band and is most against 868MHz frequency band as shown in figure 8.

D. Channel Access Failure Probability

Channel access is reported failure when node could find the channel idle for two consecutive times within its maximum allowed backoff stages(maxcsmabackoff) as described in section-II. It can be calculated as follows.

$$p_{cf} = \frac{x^{m+1}(1-y^{n+1})}{(1-y)} \quad (14)$$

Here P_{cf} = Probability of Channle access failure
m= macMaxcsmabackoff
x = $\alpha + (1-\alpha)\beta$
$y = P_{fail}(1-x^{m+1})$

the equation shows that channel access failure probability mainly depends upon the values of α, β and macMaxcsmabackoff. Higher the probability of carrier sensing busy, higher will be the probability of channel access failure. As these values increases with the increase in load so the same trend is being reflected here. The results shown in fig.9 verifies it.

E. Packet Failure due to retry limits

When transmitting node does not receive acknowledgement against its transmitting packet within the macAckWaitDuration then it retransmit the frame again. The transmission is reported

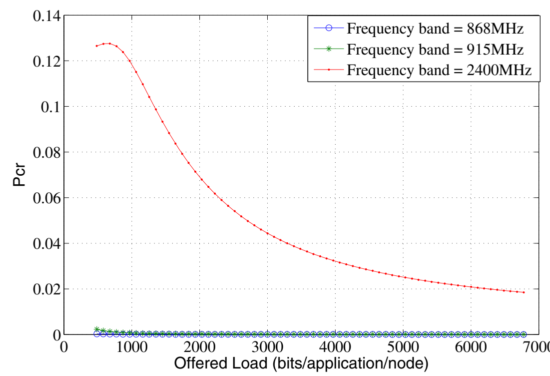

Fig. 10. *Failure Transmission due to retry limits*

failure when number of retries limit increases the value of macMaxFrameRetries. Chances of transmission failure are very low as can be seen from the fig.10.

F. Reliability

Reliability is calculated as number of packets reached its destination successfully. There are two possibilities that packets could not be reached at its destination. 1. the packet may be exhausted in the buffer of sender as it could not find the channel access idle. 2. Failure probability after exceeding retry limits (Pcr). The situation happens when node could not receive the frame acknowledgement within its specified time and retry limits exceeds the value of macFrameRetries as explained in section III.

The reliability is calculated by subtracting both of these probabilities by following equation.
$Reliabilty = 1 - (P_{cf}+P_{cr})$
Reliability is quite high with smaller loads and it decreases with the increase in load as shown in fig.11. The impact of different frequency bands is expected as it is inversally proportional to the the failure probability.

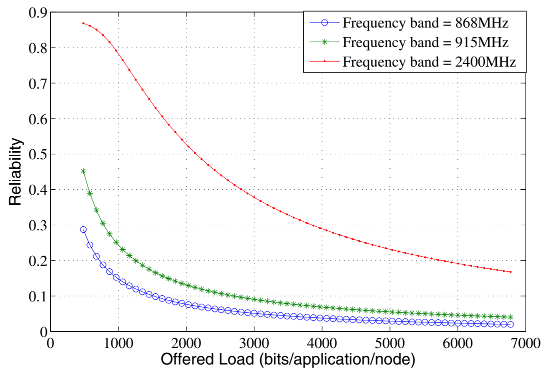

Fig. 11. *Reliability of different frequency bands*

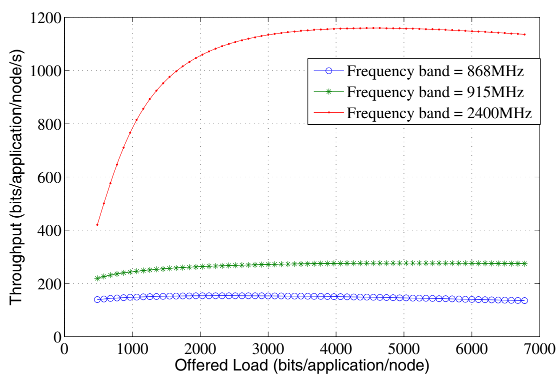

Fig. 12. *Throughput of different frequency bands*

G. Throughput against each Frequency Channel

Throughput is defined as time required for successful transmission of packets from source to destination Throughput against applied load is calculated by simply multiplying the probability of successful transmitted packets with the applied load of 10 nodes. The results in fig.12 show that throughput against 2.4GHz frequency band is much higher than other two frequency bands.

VI. Conclusion and Future Work

In this paper, we have evaluated a performance of Contention Access Period of IEEE 802.15.4 standard in three different frequency modes. Effect of same load variation in different frequency bands has been analyzed in respect of finding the busy channel probability during CCA1, CCA2, failure probability, reliability and throughput. Simulation results show that performance during 2.4GHz band is considerably better than other two frequency bands whereas increase in load severely effects the reliability during CAP.

In future work, we want to examine the performance measures of IEEE802.15.4 standard when we change the default parameters and want to analyze the best parameters for different loads offered.

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