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Throughput of Customised ZigBee Stack- A Mathematical Modelling

A.Narmada, P.Sudhakara Rao

Abstract— ***Research work is being done in the field of wireless communication protocols in order to find the desired applicability suitable to the end user. ZigBee protocol is chosen due to its reliable, long range and robust communication. In this direction there is need of designing a common communication protocol to realize a virtual control network by customizing the existing ZigBee protocol stack. It is also required to embed internet support protocols in different layers of the proposed stack so as to enable the entire network with internet connectivity.***

The proposed application aims at interoperating different devices under user personal area network, this fact has led to propose a new protocol stack with which every device of the network can be easily operated or controlled with enhanced network capabilities like resource sharing, additional middle layer for realising the proposed application using WPAN christened as ZigBee IP [ZI] stack.

ZI stack is designed and the corresponding mathematical modelling is done in order to find better stack than ZigBee. This paper presents the design and modelling of throughput which is one of the important design parameters. Both the stacks viz., ZI and ZigBee are also compared w.r.t throughput.

Keywords— ***Non real Time, Real Time, ZigBee, ZigBee- IP stack, mathematical modelling.***

I. INTRODUCTION

Keeping in view about the need of the proposed work that needs a reliable communication protocol stack, both the stacks viz., TCP/IP and WPAN are to be studied in depth so as to modify the stacks in order to accommodate the proposed application. Very slow response, lower sized data packets, over head etc are the disadvantages of the original ZigBee stack. TCP/IP protocol stack is bearing higher memory foot print thus making is not suitable to small sized networks. Hence a new stack is proposed so as to minimize the latency, enhance the data rates and to improve the response time. The throughput analysis and mathematical modelling of newly designed stack christened ZI stack is published in this paper along with the experimentation results**.** The throughputs of ZI and ZigBee stacks are compared and tabulated here.

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* Correspondence Author

Dr.A.Narmada*, Professor, ECE, Sridevi Women's Engineering College, Hyderabad, Telangana, India. narswec2019@gmail.com

Dr.P.Sudhakara Rao, Professor, ECE, G.Narayanamma Institute Of Technology And Science ,Hyderabad, Telangana, India. sparvata@gmail.com

IEEE 802.15.4 standard ZigBee stack is shown in figure 1 with four layers namely physical, Medium Access control, Network, and Application layers. The major functionalities of physical layer include bit timing, voltage levels, mode of transmission, coding techniques used etc. Physical layer uses DSSS technique to avoid unwanted noise [1-10].

A controlled access to medium is provided by MAC layer with the help of sensor MAC protocol. This layer is a hop-to-hop layer which provides framing, error control at each hop till destination. An Adhoc On-demand Distance Vector Routing Protocol is employed the next higher layer i.e. network layer. The network layer provides end to end route based on AODV protocol but this layer suffers with higher transmission delay due to coordinator involvement in every small data transfer in order to provide reliable data transfer. Further research is to be carried out in order to find an efficient communication protocol with better throughput as an alternative to the original ZigBee stack. Very easy user interface is provided by the application layer with the ZigBee Device Object corresponding to every node of the network.

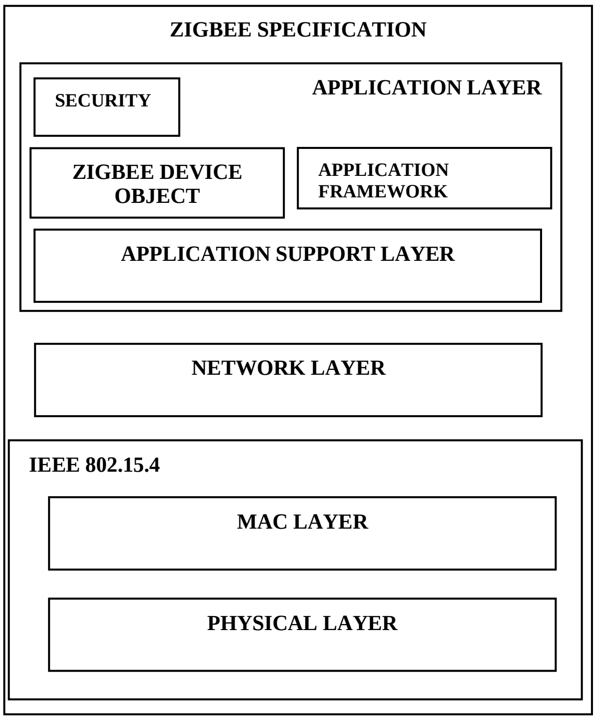

Figure1. ZigBee stack

II. MOTIVATION

The integration of WPAN and IP attracts plenty user applications that leading to many advantages. The following points are to be addresses during this integration.

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- Lower data rates of ZigBee protocol set versus Higer data rates of IP protocol set
- Addressing schemes of both are different.
- Packet formats
- Header overheads
- Higher memory foot prints of IP stack

It is not enough if one stack is modified to incorporate the other stack. There is need of middleware to interoperate both stacks ever after customization of the Zigbee stack and to achieve optimum memory foot prints by overcoming the challenges listed above due to the reason that a small embedded system of WSN node is fully resource constraint. Hence there is a need to customize the ZigBee stack with optimal resources [11-20].

III. RELATED WORK

Many applications adapted wireless communication based on IEEE 802.15.4 ZigBee protocol as it offers is low cost, robust and reliable data transfer between source and destination [1-3]. The need of customization of ZigBee stack to suit IP based communication attracts in depth mathematical modelling and analysis as it is more advantageous in various user applications [4-10]. The mathematical analysis is to be carried out in such a way that the output parameters are more efficient and nearly close to ideal values. The analysis also to be carried out w.r.t experimental values, theoretical as well as experimental values is to be compared for better performance of the system. The performance of ZigBee protocol is degraded due to interference noise in the presence of other communication protocols such as Bluetooth, wi-fi etc [10-16].

Unnecessary interference is caused by the node association in the networks based on IEEE 802.15.4 protocol, and hence there is need for optimization [11].

The major concern in WPAN is higher power consumption in small WSN nodes. Different chipsets are used to analyse the power consumption during transmission and reception [12].

The power consumed by various wireless protocols such as UWB, Wi-Fi, and Bluetooth is nearly ten times than that of ZigBee power consumption.

The environmental effect is not considered while analysing the performance of IEEE 802.15.4 standard MAC layer with respect to CSMA/ CA algorithm [12-17]. NS-2 simulator is used with 2D Marcov chains to analyse the system performance in non beaconed and beaconed mode of transmission.

The values of throughput for scenarios with varying number of nodes from 5 to 30 under varying traffic loads and hops are tabulated [18]. However there is a need for mathematical analysis in order to study the performance of the different types of ZigBeee devices [19-27].

IV. MATHEMATICAL MODELLING OF THROUGHPUT OF CUSTOMISED ZIGBEE (ZI) STACK

The mathematical concepts and equations of a system are described by its mathematical model. The study of different properties of a system is predicted by its behaviour. Different mathematical models are available for use and are chosen based on the system requirements, these models compensate for the gap between theoretical and experimental values. Complex equations and multiple outputs are required for statistical modelling thus empherical modelling is used in the proposed work to comprehend easily. Figure 2 depicts the newly designed ZigBee- IP stack christened as ZI stack with adaptation layer between network layer and application layers [21-27]. Physical layer, MAC layer, Network layer, Adaptation layer and Application layer are part of ZI stack numbered from 1 to 5 respectively. Direct sequence spread spectrum technique is employed by the physical layer of ZI similar to the physical layer of ZigBee stack.

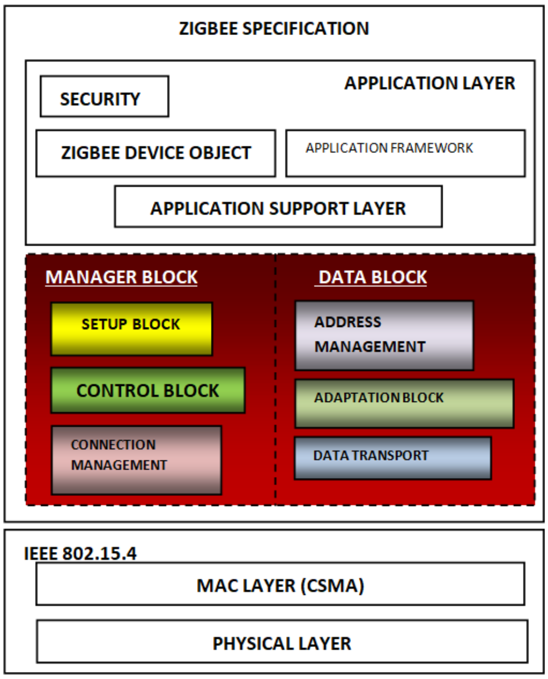

Figure 2: ZI stack(Customized ZigBee Stack)

The protocol of Medium access control sub layer of ZigBee stack is changed to CSMA while keeping all other functionalities same as that of ZigBee MAC layer. The protocol of network layer of ZigBee stack is changed to Routing Information Protocol version 2 while keeping all other functionalities same as that of ZigBee network layer. The experimentation is carried out using different types of scenarios and this paper publishes the experimentation results of 5 such scenarios with 5, 10, 15, 20, 25 and 30 nodes by varying loads and hops. The application layer of ZigBee stack is changed by adding ZDIs corresponding to newly designed WSN nodes [21].

Figure 2 shows the throughput of the customised Zigbee stack and defined as the ratio of number of received data bits to the total number of bits sent, measured in bits per second.

The variables used in the model are briefly presented here for reference

BOi : Back off variable (0 to 15)

T_{TA}RxTxTurnaroundTime**:**The time consumed by the physical layer to switch from receive mode to transmit mode.

S_P: Preamble of sender.

$L_{\textbf{Frame}}$: Frame length in Bytes.

N: No. of Users

P_{Tx}: Transmit mode power consumption

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P_d: Packet reception probability.
S_{al}: Time required to listen to Acknowledgement
P_S: Sleep mode power consumption
R_a: Time required to transmit an acknowledgement
R_{qpl}: Post packet reception delay for queuing
R_d: Time required to receive data frame
R_s: Sleep period of receiver
R_l: Listen period of receiver
S_d: time to transmit data.
P_{Rx}: Receive power consumption

(A) ZI Stack: A Mathematical model for Throughput

The time required to transmit a frame of 'X' bytes is denoted by $T_{Frame}(x)$ as per equation (1).

$$T_{Frame}(x) = \frac{8*(L_{PHY} + L_{MAC\_HDR} + L_{ADDRESS} + L_{NW\_HDR} + L_{ML\_HDR} + L_{MAC\_FTR} + X)}{R_{Data}}$$

---(1)

Where
L_{PHY}= 6; Length of the PHY header in bytes
L_{MAC_HDR} = 3; Length of the MAC header in bytes
L_{MAC_FTR} = 2; Length of the MAC footer in bytes
$L_{ADDRESS}$ = 16; length of address fields in bytes
L_{NW_HDR}= 10; Length of the NWK layer Header
L_{ML_HDR}= 8; Length of the Adaptation layer Header
X= Length of data (51 bytes maximum)
R_{data}= 250Kbps ; Raw data rate

Let 'N' denote the number of users in the network of consideration, then the time of signal collision between N couple users with probability of collision $t_{colldev}$is given by

$t_{colldev}$= $2*T_{Frame}/N$ ------(2)

It is required to calculate the slot time inorder to estimate the delay in transmission. The slot time can be expressed as the sum of clear channel assessment time, time consumed by the transmitter to switch from receive mode to transmit mode is denoted by RxTxTurnaroundTime, Propagation delay and MAC layer processing delay as given by equation (3).

$$SlotTime = CCATime + RxTxTurnaroundTime + AirPropagationTime + MacProcessingDelay \text{ -------(3)}$$

The probability of an idle slot in case of 'n' stations is given by equation 4

$$P_i = (1-\tau)^{n-1} \text{ -------(4)}$$

Where τ = The probability that a given station attempts to transmit in the slot.

The probability of collision between two stations is given by $P_c = 1-(1-\tau)^{n-1}$ -----(5)

Where $\tau = 1-(1-P_c)^{\frac{1}{n-1}}$ ----(6)

The station follows exponential back off algorithm in case of a collision. The exponential back off parameters are W and m, W is minimum value of Back off variable BO_{min} and BO_{max}= $2^m BO_{min}$. BO_{min}=1, BO_{max}=16.

$$m = \log_2\left(\frac{BO_{max}}{BO_{min}}\right) \text{ ----(7)}$$

From [20]

$$\tau = \frac{2(1-2P_c)}{((1-2P_c)(W+1)+P_cW(1-2P_c^{\ m})} \text{ -----(8)}$$

Substitute eq.8 in 5 and solving for 'n' as per equation (9).

$$n = f(P_c) = 1 + \frac{\log(1-P_c)}{\log\left(1-\frac{2(1-2P_c)}{((1-2P_c)(W+1)+P_cW(1-2P_c^{\ m}))}\right)}$$

--------(9)

When simplified after mathematical approximations P_c as a function of number of nodes 'n' is given by equation 10.

$$P_c(n) = \frac{(2^n-2)+0.8*2^n}{2^{n+1}*BO_{min}+n} \text{ ---(10)}$$

The time required to transmit a frame of 'X' bytes $T_{Frame}(x)$ is the sum of all the data and header bytes divided by the data rate R_{data}as given by the equation (11)

$$T_{Frame}(x) = \frac{8*(L_{PHY} + L_{MAC\_HDR} + L_{ADDRESS} + L_{NW\_HDR} + L_{ML\_HDR} + L_{MAC\_FTR} + X)}{R_{data}}$$

..(11)

Let T_{ACK} be the time to receive an acknowledgement which is the time taken to receive only header part of acknowledgement and given by equation (12) [20]

$$T_{ACK} = \frac{8*(L_{PHY} + L_{MAC\_HDR} + L_{MAC\_FTR} + L_{NW\_HDR} + L_{ML\_HDR})}{R_{data}}$$

-------(12)

$$T_{IFS}(X) = AIFSN[AC]*SlotTime + RxRFDelay + RxPLCPDelay + MacProcessingDelay + RxTxTurnaroundTime. \text{ - - - - - (13)}$$

AIFS: Arbitration IFS shall be used to transmit the data frames (MPDUs), the management frames (MMPDUs) and the control frames.
RxRFDelay is the time needed by the PMD layer to deliver a symbol to the PLCP layer.
RxPLCPDelay is the time needed by the PLCP layer to deliver a bit to the MAC layer.

The AIFS parameter set for 2.4 GHz band is shown in table 1 for different types of data [21]. However, only the audio data is chosen for experimentation because transmission of audio data over the WSN is simple.

Table 1 AIFS Parameters

AC	AIFSN	AIFS
AC_BK	7	73 -360 µs
AC_BE	3	37 -70 µs
AC_VI	2	28 -50 µs
AC_VO	2	28- 50 µs

where

- BK represents BACK GROUND noise.
- BE represents BEST EFFORT signal.
- VO represents VOICE or audio data.
- VI represents VIDEO data.

Let T_{BO} denote backoff time to wait in case of collision which depends on the probability of collision(Pc(N)), the slot time and the random number R chosen in back off algorithm as given by equation (14), (15) .

$$T_{BO} = SlotTime * R * P_c(N) \text{ ----(14)}$$

$$R = Rand[0, 2^{BOi} - 1] \text{ ----(15)}$$

$T_{BO\ Max}$ = SlotTime * R_{Max}* $P_c(N)_{Max}$

BO is backoff variable.

Hence the end-to-end delay cane be expressed as in equation (16)

$$Delay(X) = T_{BO} * P_c(N) + T_{Frame}(X) + T_{TA} + T_{ACK} + T_{IFS}(X) \quad \text{-----(16)}$$

The table 2 [22] shows the parameters used in the model and their measured or standard values as per the specifications. Throughput depends on probability of collision, number of nodes, length of the frame, time due to collision and delay.

The time for transmitting one packet is divided by sum of other packets times the time of transmitting one packet and the time of signal collision of N users times the probability of signal collision is equal to **UTILIZATION** ρ_{Frame}

Hence

$$\rho_{Frame} = \frac{Delay(X)}{Delay(X) + P_c(N) * t_{colldev} * N} \quad \text{---------(17)}$$

Throughput is expressed as length of the frame divided by the delay times the utilization factor as given by equation (20).

$$Throughput = \rho_{Frame} * \frac{L_{Frame}}{Delay(X)} \quad \text{----(18)}$$

ρ_{Frame} = Utilization factor

L_{frame} = length of the frame.

The Delay(x) is the time required to transmit a frame of 'x' bytes. Hence throughput can be expressed as length of the frame divided by the delay due to (N-1) nodes and time of probability of collision due to N nodes as given by the equation (19).

$$Throughput = \frac{L_{Frame}}{Delay(X) + P_c(N) * t_{colldev} * (N-1)} \quad \text{------(19)}$$

V. EXPERIMENTAL SETUP AND RESULTS

The experimental work is carried out using Qualnet Network simulator 4.0.2. The number of nodes is chosen from 5 to 30 under different scenarios of simulation because it is assumed that a typical WPAN of home network may not consist of devices more than 30. Table 3 [20] lists the specifications of the experimentation setup and performance metrics. The experimentation is done for real time and non real time traffic for the ZigBee as well as the ZI stack for 5 nodes to 30 nodes by varying loads from 13000 packets to 20200 packets and hops from 1 to 10 in three steps with step size of 4. The results are tabulated in tables 4 to 11. The seed is set to 3 milli sec and simulation time set as 55 seconds. Both the ZigBee and the ZI stacks are compared for Constant Bit Rate (CBR, also termed as Non Real Time traffic (NRT)) as well as variable bit rate (VBR, also termed as Real Time Traffic (RT)) data traffic by varying load and hops and the results are published and compared. The MicaZ mote is chosen for experimentation.

Table 2. Parameters Used In The Model And The Respective Values

Parameter	Value	Parameter	Value
BO_i	0 to 15	Ps	30µW (Device specific)
T_{TA}	<=4µsec	$R_{a\ (measured)}$	15 µsec
$S_{p(measured)}$	0.2 µsec	R_{qpl}	1sec(Measured)
T_{IFS}	360 µsec	R_d	4.064m sec (app. Specific)
L_{Frame}	127 Bytes	R_s	0.1 milli sec(measured)
N	1 to 50	R_l	1 µsec(R_l>S_p)
P_{RX}	56.5mW(Device specific)	S_d	4.064msec(App. Specific)
P_d	0 to 1	P_{TX} (Device specific)	48mW
S_{al}	20 µsec (Shortest schedulable interval (S_{al}>R_a)	Slot time	20 µsec

Table 3. Experimental Setup

S.N	Parameter	Value
i.	Packet interval time	0.1 milli sec
ii.	Seed	3
iii.	Number of nodes	5 to 30
iv.	Near	1-Hop
v.	Medium	3-hops
vi.	Far	8-hops
vii.	Low	15000 packets
viii.	Medium	18000 packets
ix.	High	20200 packets
x.	Simulation Time	55 Sec
xi.	terrain size	100m x 100m
xii.	Routing Protocol	RIP
xiii.	Packet Size	51 Bytes
	Performance Metrics	
i.	Throughput (bits per sec)	

Table 4. Throughput (kbps) Vs Load- Real time Traffic, Load(No.of packets)*1000

N	S	13	14	15	16	17	18	19	20.2
5	ZB	110	118	119	105	108	116	117	109
	ZI	101	100	102	107	106	104	109	110
10	ZB	117	106	119	118	120	119	120	118
	ZI	103	101	105	105	104	106	108	109
15	ZB	117	120	120	119	120	121	120	120
	ZI	107	104	105	105	105	106	106	107
20	ZB	116	117	118	118	119	119	120	121
	ZI	100	105	105	106	106	107	108	108
25	ZB	112	120	122	124	124	124	123	124
	ZI	103	103	105	102	109	107	108	105
30	ZB	113	119	120	118	123	117	123	119
	ZI	103	102	104	106	108	107	108	104

Table 5. Throughput (KBps) Vs Load- Non Real Time Traffic, Load(No.of packets)*1000

N	S	13	14	15	16	17	18	19	20.2
5	ZB	118	120	120	120	119	120	119	120
	ZI	104	105	106	107	107	108	109	110
10	ZB	117	120	120	120	120	120	120	120
	ZI	104	104	105	105	106	106	108	108
15	ZB	117	120	120	120	120	120	120	120
	ZI	104	104	105	105	105	106	106	107
20	ZB	116	117	118	118	119	119	120	121
	ZI	104	105	105	106	106	107	108	108
25	ZB	119	120	122	124	124	124	123	124
	ZI	103	103	105	106	106	107	108	109

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30	ZB	119	119	120	124	123	124	123	124
	ZI	103	102	104	106	106	107	108	109

Table 6. Throughput (KBps) Vs Hops

N	S	1-Hop		5-Hops		10-Hops	
		NRT	RT	NRT	RT	NRT	RT
5	ZB	110	109	110	108	110	109
	ZI	110	101	110	104	110	105
10	ZB	109	110	108	108	110	110
	ZI	109	104	108	110	110	105
15	ZB	108	108	108	107	108	108
	ZI	108	105	108	105	108	104
20	ZB	106	106	104	104	103	103
	ZI	106	102	104	101	103	103
25	ZB	100	109	100	100	100	100
	ZI	106	103	104	105	103	104
30	ZB	106	100	103	99	102	101
	ZI	100	104	100	103	100	105

LEGEND:

ZI: Zigbee-Ip stack, ZB: ZigBee stack
NRT: Non-Real Time traffic
RT: Real Time Traffic

VI. COMPARISON AND CONCLUSION

From the results as tabulated in table 5, it is observed that the maximum values of throughput vs load of ZI and ZigBee stacks in case of non real time traffic are 124 kbps sec and 102 kbps sec respectively. Theoretical value of delay from the mathematical analysis is 250 kbps for ZigBee and 127 kbps for ZI for the packet size of 51 bytes as shown in table 7.

Table 7. Performance Comparison

KBPS	ZigBee	ZI	Variation
Theoretical value	250	127	-49.26%
Maximum Practical value(NRT)	124	102	-17.74%
Maximum Practical (NRT)	124	100	19.35%

The following conclusions can be drawn from the results as tabulated in tables 4, 5, 6 and 7

1. There is -49.26% variation of throughput of ZI stack w.r.t ZigBee stack in case of theoretical values.
2. There is -17.74% variation of throughput of ZI stack w.r.t ZigBee stack in case of practical value of non real time traffic.
3. There is -19.35% variation of throughput of ZI stack w.r.t ZigBee stack in case of practical value of real time traffic.

The empirical model is used to start with as it is very simple and hence the parameters could not be modelled exactly. More suitable mathematical model like statistical equation modelling could be developed for better suitability.

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AUTHORS PROFILE

Dr.A.Narmada had completed her Ph.D(2015) in wireless communication from JNTU Hyderabad, M.E(2005) from Osmania University and B.Tech (1998) from Nagarjuna University. She has 21 years of teaching and research experience and published 29 research papers in various international conferences and journals. Currently she is working with SRIDEVI WOMEN'S ENGINEERING COLLEGE, HYDERABAD, TELANGANA, INDIA as a Professor and Head of the Department, ECE

Dr.P.Sudhakara Rao, working with G.NARAYANAMMA INSTITUTE OF TECHNOLOGY AND SCIENCE, HYDERABAD, TELANGANA, INDIA as Professor and Dean R&D. He has got a wide research experience of 38 years and published plenty of research papers in IEEE, various other international conferences and SCOPUS Journals. He had completed Ph.D (2003) from ANNA University in Image Processing, M.E (1988) from ANNA University and B.Tech (1977) from University of MYSORE.

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