Throughput of Customised ZigBee Stack- A Mathematical Modelling

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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 inter-operating 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. 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 DSST 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.

Figure 1. ZigBee stack

IEEE 802.15.4
MAC LAYER

APPLICATION FRAMEWORK
APPLICATION SUPPORT LAYER
NETWORK LAYER
ZIGBEE DEVICE OBJECT
APPLICATION LAYER
SECURITY

ZIGBEE SPECIFICATION

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.

- Lower data rates of ZigBee protocol set versus Higher 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 even 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 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 Markov 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 ZigBee 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.

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<sub>TA</sub>RxTxTurnaroundTime: The time consumed by the physical layer to switch from receive mode to transmit mode.
S<sub>P</sub>: Preamble of sender.
L<sub>Frame</sub>: Frame length in Bytes.
N: No. of Users
P<sub>T</sub>: Transmit mode power consumption
P<sub>R</sub>: Packet reception probability.
S<sub>T</sub>: Time required to listen to Acknowledgement
P<sub>S</sub>: Sleep mode power consumption
R<sub>T</sub>: Time required to transmit an acknowledgement
R<sub>Q</sub>: Post packet reception delay for queuing
R<sub>D</sub>: Time required to receive data frame
R<sub>R</sub>: Sleep period of receiver
R<sub>L</sub>: Listen period of receiver
S<sub>T</sub>: time to transmit data.
P<sub>R</sub>: Receive power consumption

![Figure 2: ZI stack(Customized ZigBee Stack)](image-url)
(A) ZI Stack: A Mathematical model for Throughput

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

$$T_{\text{Frame}}(x) = \frac{8 * (L_{\text{PHY}} + L_{\text{MAC_HDR}} + L_{\text{ADDRESS}} + L_{\text{NW_HDR}} + L_{\text{ML_HDR}} + L_{\text{MAC_FTR}} + X)}{R_{\text{data}}}$$. 

---(1)

Where

- $L_{\text{PHY}} = 6$: Length of the PHY header in bytes
- $L_{\text{MAC_HDR}} = 3$: Length of the MAC header in bytes
- $L_{\text{MAC_FTR}} = 2$: Length of the MAC footer in bytes
- $L_{\text{ADDRESS}} = 16$: Length of address fields in bytes
- $L_{\text{NW_HDR}} = 10$: Length of the NWK layer Header
- $L_{\text{ML_HDR}} = 8$: Length of the Adaptation layer Header
- $X$: Length of data (51 bytes maximum)
- $R_{\text{data}}$: 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 $t_{\text{collide}}$ is given by

$$t_{\text{collide}} = 2 \times T_{\text{Frame}} / N$$. 

---(2)

It is required to calculate the slot time in order to determine 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).

$$\text{SlotTime} = \text{CCATime} + \text{RxTxTurnaroundTime} + \text{AirPropagationTime} + \text{MacProcessingDelay}$$. 

---(3)

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

$$P_1 = (1 - \tau)^n - 1$$. 

---(4)

Where $\tau$ is the probability that a given station attempts to transmit in the slot.

The probability of collision between two stations is given by

$$P_c = 1 - (1 - \tau)^2 - 1$$. 

---(5)

Where $\tau = 1 - (1 - P_{c})^{\frac{1}{n}}$ 

---(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 $B_{\text{Omin}}$ and $B_{\text{Omax}} = 2^m B_{\text{Omin}}$. $B_{\text{Omin}} = 15$, $B_{\text{Omax}} = 16$.

$$m = \log_2 \left( \frac{B_{\text{Omax}}}{B_{\text{Omin}}} \right)$$. 

---(7)

From (20)

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

---(8)

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

$$n = f(P_c) = 1 + \frac{\log(1 - P_c)}{\log(1 - (1 - 2P_c)/(W + 1) + P_c W (1 - 2P_c)^m))}$$. 

---(9)

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

$$P_c(n) = \frac{(2^n - 2) + 0.8 \times 2^n}{2^{n+1} * B_{\text{Omin}} + n}$$. 

---(10)

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

$$T_{\text{Frame}}(x) = \frac{8 * (L_{\text{PHY}} + L_{\text{MAC_HDR}} + L_{\text{ADDRESS}} + L_{\text{NW_HDR}} + L_{\text{ML_HDR}} + L_{\text{MAC_FTR}} + X)}{R_{\text{data}}}$$. 

---(11)

Let $T_{\text{ACK}}$ be the time to receive an acknowledgement which is the time taken to receive only header part of acknowledgement and given by equation (12) [21]

$$T_{\text{ACK}} = \frac{8 * (L_{\text{PHY}} + L_{\text{MAC_HDR}} + L_{\text{MAC_FTR}} + L_{\text{NW_HDR}} + L_{\text{ML_HDR}})}{R_{\text{data}}}$. 

---(12)

$$T_{\text{IFS}}(X) = \text{AIFS}[\text{AC}] * \text{SlotTime} + \text{RxRFDelay}$$. 

+ $\text{RxPLCPDelay} + \text{MacProcessingDelay} + \text{RxTxTurnaroundTime}$. 

---(13)

AIFS: Arbitration IFS shall be used to transmit the data frames (MPDUs), the management frames (MMPDUs) and the control frames.

$\text{RxRFDelay}$ is the time needed by the PMD layer to deliver a symbol to the PLCP layer.

$\text{RxPLCPDelay}$ 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**

<table>
<thead>
<tr>
<th>AC</th>
<th>AIFS</th>
<th>AIFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC_BK</td>
<td>7</td>
<td>73.360 µs</td>
</tr>
<tr>
<td>AC_BE</td>
<td>3</td>
<td>37.700 µs</td>
</tr>
<tr>
<td>AC_VI</td>
<td>2</td>
<td>28.500 µs</td>
</tr>
<tr>
<td>AC_VO</td>
<td>2</td>
<td>28.500 µs</td>
</tr>
</tbody>
</table>

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($P_c(N)$), the slot time and the random number $R$ chosen in back off algorithm as given by equation (14), (15).

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

---(14)

$$R = \text{Rand}[0, 2^{BO_{\text{Max}}}] - 1$$ 

---(15)

$$T_{BO_{\text{Max}}} = \text{SlotTime} * R_{\text{Max}} * P_c(N_{\text{Max}})$$

BO is backoff variable.

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

$$\text{Delay}(X) = T_{BO} + T_{\text{Frame}}(X) + T_{\text{ACK}} + T_{\text{IFS}}(X)$$ 

---(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 \( \rho_{\text{Frame}} \)

\[
\rho_{\text{Frame}} = \frac{\text{Delay}(X)}{\text{Delay}(X) + P_c(N) \cdot t_{\text{collide}} \cdot N}
\]

Hence

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

\( \rho_{\text{Frame}} \), Utilization factor

\( L_{\text{Frame}} \), 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 = \( \frac{L_{\text{Frame}}}{\text{Delay}(X) + P_c(N) \cdot t_{\text{collide}} \cdot (N-1)} \) -----(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 sec. Both Zigbee and 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BO</td>
<td>0 to 15</td>
</tr>
<tr>
<td>PS</td>
<td>30µW (Device specific)</td>
</tr>
<tr>
<td>( T_{\text{ps}} )</td>
<td>15 µsec</td>
</tr>
<tr>
<td>( R_{\text{m}} )</td>
<td>1 sec (Measured)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>360 µsec</td>
</tr>
<tr>
<td>( L_{\text{frame}} )</td>
<td>127 Bytes</td>
</tr>
<tr>
<td>( R_a )</td>
<td>0.1 mili sec(measured)</td>
</tr>
<tr>
<td>( N )</td>
<td>1 to 50</td>
</tr>
<tr>
<td>( R_a )</td>
<td>1 mili sec(RCS)</td>
</tr>
<tr>
<td>( P_{\text{x}} )</td>
<td>56.5mW(Device specific)</td>
</tr>
<tr>
<td>( S_0 )</td>
<td>4.064msec(App. Specific)</td>
</tr>
<tr>
<td>( S_0 )</td>
<td>48mW</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>20 µsec (Shortest)</td>
</tr>
</tbody>
</table>

Table 3. Experimental Setup

<table>
<thead>
<tr>
<th>S.N</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>i.</td>
<td>Packet interval time</td>
<td>0.1 milli sec</td>
</tr>
<tr>
<td>ii.</td>
<td>Seed</td>
<td>3</td>
</tr>
<tr>
<td>iii.</td>
<td>Number of nodes</td>
<td>5 to 30</td>
</tr>
<tr>
<td>iv.</td>
<td>Near</td>
<td>1-Hop</td>
</tr>
<tr>
<td>v.</td>
<td>Medium</td>
<td>3-hops</td>
</tr>
<tr>
<td>vi.</td>
<td>Far</td>
<td>8-hops</td>
</tr>
<tr>
<td>vii.</td>
<td>Low</td>
<td>15000 packets</td>
</tr>
<tr>
<td>viii.</td>
<td>Medium</td>
<td>18000 packets</td>
</tr>
<tr>
<td>ix.</td>
<td>High</td>
<td>20200 packets</td>
</tr>
<tr>
<td>x.</td>
<td>Simulation Time</td>
<td>55 Sec</td>
</tr>
<tr>
<td>xi.</td>
<td>terrain size</td>
<td>100m x 100m</td>
</tr>
<tr>
<td>xii.</td>
<td>Routing Protocol</td>
<td>RIP</td>
</tr>
<tr>
<td>xiii.</td>
<td>Packet Size</td>
<td>51 Bytes</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>N</th>
<th>S</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>ZB</td>
<td>118</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>119</td>
<td>120</td>
<td>119</td>
<td>120</td>
</tr>
<tr>
<td>ZI</td>
<td>104</td>
<td>105</td>
<td>106</td>
<td>107</td>
<td>110</td>
<td>107</td>
<td>108</td>
<td>109</td>
<td>110</td>
</tr>
<tr>
<td>10</td>
<td>ZB</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
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<td>ZI</td>
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<td>105</td>
<td>106</td>
<td>107</td>
<td>108</td>
</tr>
<tr>
<td>20</td>
<td>ZB</td>
<td>115</td>
<td>115</td>
<td>115</td>
<td>115</td>
<td>115</td>
<td>115</td>
<td>115</td>
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</tr>
<tr>
<td>ZI</td>
<td>103</td>
<td>104</td>
<td>105</td>
<td>106</td>
<td>107</td>
<td>108</td>
<td>109</td>
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<td>110</td>
</tr>
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<td>30</td>
<td>ZI</td>
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<td>113</td>
<td>113</td>
<td>113</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>N</th>
<th>S</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20.2</th>
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</thead>
<tbody>
<tr>
<td>5</td>
<td>ZB</td>
<td>118</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>119</td>
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</tr>
<tr>
<td>ZI</td>
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<td>106</td>
<td>107</td>
<td>108</td>
<td>109</td>
<td>108</td>
<td>109</td>
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<tr>
<td>10</td>
<td>ZB</td>
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<td>117</td>
<td>117</td>
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<tr>
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<td>108</td>
<td>109</td>
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</tr>
<tr>
<td>ZI</td>
<td>104</td>
<td>105</td>
<td>106</td>
<td>107</td>
<td>108</td>
<td>109</td>
<td>108</td>
<td>109</td>
<td>110</td>
</tr>
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<td>20</td>
<td>ZB</td>
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<td>30</td>
<td>ZI</td>
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</tr>
</tbody>
</table>

Table 6. Throughput (KBps) Vs Load-Non Real Time Traffic, Load(No.of packets)*1000
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>
<thead>
<tr>
<th>N</th>
<th>S</th>
<th>1-Hop</th>
<th>5-Hops</th>
<th>10-Hops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NR</td>
<td>RT</td>
<td>NR</td>
</tr>
<tr>
<td>5</td>
<td>ZB</td>
<td>110</td>
<td>108</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>ZI</td>
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<td>104</td>
<td>110</td>
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**Table 6. Throughput (Kbps) Vs Hops**

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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Throughput of Customised ZigBee Stack - A Mathematical Modelling


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