CHAPTER 3

STATISTICAL ANALYSIS OF QoS IN WSN UNDER CROSS-LAYER FRAMEWORK

This chapter presents the correlation between QoS (Energy, Throughput, Delay and SNR) and AMP (Application, MAC and Physical layer) parameters using a statistical model for Wireless Sensor Networks over IEEE 802.15.4. The multivariate regression analysis that predicts the significant contribution of AMP parameters towards QoS of WSN over IEEE 802.15.4 was modeled. Based on the outcome of statistical correlation and multivariate prediction model, the respective QoS correlated AMP parameters were tuned to attain trade-off among QoS.

3.1 INTRODUCTION

In recent years, the rapid growth of applications of wireless sensor networks such as voice, image, video, etc., has shed much light on various requirements on energy efficiency, throughput, end-to-end delay and SNR to achieve reliable and acceptable Quality of Service (Marwan Al-Jemeli & Fawnizu 2015; Elkashlan et al. 2014). The power consumption poses a critical challenge in the design of the deployment of the networks and protocols in wireless sensor networks (Amritpal Kaur et al. 2014; Khan et al. 2014). Hence short range communication based WSN applications considered the combined framework of Physical and MAC layer of IEEE 802.15.4 over ZigBee making Beacon modes of operation to prolong the lifetime of the network (Chandane et al. 2012). This IEEE 802.15.4 over ZigBee-based networks has received much attention, with a focus on performance...
characterization regarding low energy consumption applications, throughput, reliability and packet delay (Lorincz 2004). The ZigBee-based Wireless Personal area networks (WPAN) acts as two physical devices: Full function devices (FFD) and Reduced function devices (RFD). The FFD can be adopted with any topology and can talk with any other device as a network coordinator, whereas RFD can only talk with network coordinator or router (Amritpal Kaur et al. 2014; Chaudhry & Salman 2011).

In earlier research works, the performance analysis of IEEE 802.15.4 considered various routing protocols with efficient MAC protocol to overcome hidden and exposed terminal problems (Qiang & Tong 2015). To mitigate the encapsulation between the abstract layers in the OSI layer model for minimizing the energy consumption introduces the cross-layer models in various wireless and mobile networking domains (Kokkinos et al. 2013). Marwan Al-Jemeli et al. (2015) investigated a cross-layer operational model for MWSN based 802.15.4 by using application, network, MAC, and physical layers. Though a mechanism to relief communication channel between the nodes is considered by adjusting the transmission power control in physical layer but neglect the balance in attaining trade-off among QoS. Piergiuseppe & Carlo (2014) encompassed the joint selection of IEEE 802.15.4 PHY-MAC layer parameters to reduce the multiple access of interference over fading channels. Hesham ElSawy et al. (2014) proposed a multichannel design with stochastic geometry approach in 802.15.4 to utilize the spectrum in an efficient manner.

Several communication protocols in WSN used a different mechanism to improve the quality of service, but none of them have considered the strength or effects of WSN layer parameters and hence existing protocols introduce complex schemes to attain trade-off between more than two QoS parameters. Dacheng Tao et al. (2012); Idros Azrif
Manut et al. (2012) specifies the advantages of analysing the service requirements under specific scenarios using multivariate regression analysis model. At the same time, Association rule mining and multivariate regression analysis model are used together in wireless sensor networks to determine the best weather correlated parameters by comparing the pest disease parameters (Ninomiya & Kiura 2013). Similarly, multi-linear regression and statistical learning method determines the best handovers in various networks (WIMAX, GPRS, UMTS, and LTE) by estimating the correlation coefficients of parameters (RSCP, EC/NO and ABW) of those four networks (Ahmad et al. 2014). Carlos & Goncalves (2012) analyzed the performance of energy consumption, throughput, packet delivery ratio and delay over Star, Mesh and Tree topologies under IEEE 802.15.4 WPAN.

From the above analysis it is clear that the earlier works considered certain mechanisms to improve performance factors without considering the positive and negative impact of WSN layer parameters towards QoS. Hence the analysis of each parameter and their significance contribution in attaining the QoS efficiency across layers is required to support specific service of different applications. Therefore, this research work provides a model to understand the significance of each WSN layer parameters with respect to QoS under cross-layered framework to attain balance among QoS.

### 3.2 EVALUATION PARAMETERS AND METRICS

This section presents the conceptual overview of Quality of Service metrics and WSN layer (application, MAC and physical layer) parameters that influence the criticality of dynamic applications.
3.2.1 QoS Metrics

The proposed model was evaluated for the following metrics:

**Energy Consumption:** Network Lifetime of the sensor nodes depends on the energy consumption of the battery. It is measured by the average energy consumed by the nodes in the transmission of data packets (sending) and receiving in the sink. The unit of power consumption is expressed as Joule. The power consumption \((E_c)\) is represented in Equation (3.1).

\[
E_c = C_F \cdot C_R
\]

(3.1)

where, \(C_F\) is the full battery energy capacity (Initial energy), \(C_R\) is the residual battery energy (remaining energy). It is clear that the residual battery energy should be close to the full battery energy (regarding joules) so that the power consumption is minimal and optimal.

**End-to-End Delay:** The End-to-End delay metric was evaluated as the length of the time or average time spent to transfer the packet from source to destination in the network. This delay occurred due to many nodes in the network have to wait until the forwarder node wakes up or due to collisions in the network. The Equation (3.2) represents the calculation of End-to-End delay metric.

\[
E_{Delay} = \frac{\sum_{i=0}^{n} E - E_{Delay}}{n}
\]

(3.2)

where, \(\sum_{i=0}^{n} E - E_{Delay}\) is the summation of the delay of every successful packet, \(n\) is the total number of packets transmitted. However, the system should have a higher concern to the end-to-end delay metric as it might cause a system to become unstable.
**Throughput:** Throughput is the average amount of the successful data packets received at the sink node. It is measured by the (bits/Sec) or bps. Every ideal system must increase the throughput to be successful in their features.

\[
\text{Throughput} = \frac{\text{Total Number of delivered packets}}{\text{Bandwidth capacity of the network}} \tag{3.3}
\]

**SNR:** SNR is the Signal-to-Noise ratio, simply known as “SNR per bit,” i.e., Bit Error Rate (BER). It is used to measure the noise or interference, present in each successful packet of the given network and is calculated using Equation (3.4)

\[
\text{SNR} = \frac{E_b}{N_o} \tag{3.4}
\]

where, \(E_b\) is the energy associated with each user bit rate, \(N_0\) is the noise or interference in each packet.

### 3.2.2 AMP Parameters Influencing QoS for WSN

The physical parameters that are considered for the analysis of QoS metrics include Energy Threshold (ET), Transmission Power (TP) and Received Signal Strength Indicator (RSSI). The MAC parameters considered in IEEE 802.15.4 are superframe order, beacon order, MACminBE and MACmaxBE. These parameters decide the amount of data packets that can be transmitted and the length of the sleep period. The parameter that is chosen in the application layer to control QoS metrics is the packet size and the brief overview is given below.
**Energy Threshold:** It indicates activation and deactivation of the radio transceiver, energy detection and link quality indication by varying the values in dB.

**Transmit Power:** It shows the power of the network that can be increased or decreased to enhance the network connectivity among the nodes in the network and calculated by,

\[ P_T = P_I \times \frac{P_R}{P_F} \]  \hspace{1cm} (3.5)

where, \( P_T \) is the transmission power, \( P_I \) is the power consumed in the initial transmission & \( P_R \) is the residual power and \( P_F \) is the full power.

**RSSI (Received Signal Strength Indicator):** It is used to measure the power level or signal strength in the received radio signal. RSSI is usually invisible to a receiving device as the signal strength can vary and affect functionality in wireless networking communication. It is represented in Equation (3.6)

\[ RSSI = TD \times NP \]  \hspace{1cm} (3.6)

where, TD is the threshold in the QPSK/ BPSK (Quadrature Phase Shift Keying/Binary Phase Shift Keying) modulation, NP is the Noise power, which is measured by

\[ NP = NF \times TP \times BC \]  \hspace{1cm} (3.7)

\[ BC = 1.38 \times 10^{-25} \]  \hspace{1cm} (3.8)

where, NF is the Noise Factor used to measure the SNR, TP is the temperature of physical radio and BC is the Boltzmann Constant.
**Superframe Order (SO):** A coordinator can determine the work based on superframe structure. The network beacons bound this superframe and divided into equal size of the slots in the periods of activity and inactivity. Active period is further split into contention access period (CAP) and contention free period (CFP). The device can communicate during the CAP, and Guaranteed period Slot (GTS) is used for CFP. During the inactive period, the coordinator switches into power saving mode. The number of slots bounded in SO is 0 to 14.

\[ SI = SD \times 2^{SO} \]  
(3.9)

where, SI is the Superframe Interval, SD is superframe duration idle period and SO is the Superframe Order.

**BeaconOrder (BO):** BO can act as non-beacon enabled mode and beacon-enabled mode. These two modes are controlled by the structure of the super frames. If the device finds the beacon enabled mode (active slot), then it chooses the slotted CSMA/CA (Carrier sense multiple access/collision avoidance) from the duration of 0 to 14. In non-beacon enabled mode (inactive slot), the default slot is 15.

\[ BI = SD \times 2^{BO} \]  
(3.10)

where, BI is the duration between two beacons, SD is the super frame duration of inactive period and BO is the Beacon Order.

**Back off Period:** It helps to avoid collisions between the nodes by setting the waiting time for retransmission. In IEEE 802.15.4, back off period is set using two parameters like MACminBE and MACmaxBE. The backoff is expressed as follows

\[ T_{BO} = BO_{slots} \times T_{BOslots} \]  
(3.11)
where, the number of backoff slots is a random number in the interval (0, 2BE-1) with BE, then back off exponent which takes a minimum value of 3.

**MACminBE:** It is the duration of the minimum backoff slots during the CSMA/CA slots that lie in the range between 0 and 3.

**MACmaxBE:** It is the duration of the maximum backoff slots during the CSMA/CA slots that lie in the range between 4 and 8.

**Packet Size (PS):** The maximum information that is transmitted in groups as bytes is known as packet size. The IEEE 802.15.4 can support only a maximum of 127 bytes of the data unit.

### 3.3 STATISTICAL METHODS

The analysis and interpretation of collected data is carried out using statistical methods to examine the influence of individually and together. The correlation analysis and multi-variant analysis method are efficient and simple in analysing, accurately quantifying and predicting of strength and direction of relationship among variables. The procedure and applicability of those two statistical methods are briefed in the following sub-sections.

#### 3.3.1 Correlation Analysis

Correlation analysis is a statistical tool used to measure the closeness of the association between two variables. The closeness correlation is positive if the rise or decline in one variable can rise or decline the other variable (Agarwal & Saxena 2011). The correlation is negative if the rise or decline in one variable can decline or rise another variable. The linear correlation states that the amount of variation in one variable tends to bear a constant ratio to the amount of variation in the other variable. Whereas the non-linear correlation states that the amount of variation in one variable does
not tend to bear a constant ratio to the amount of variation in the other variable, then the correlation is said to be nonlinear. The Equation (3.12) is used to determine the coefficient of correlation.

Coefficient of correlation \( r = \frac{\text{Cov}(x, y)}{\sigma_x \sigma_y} \) \hspace{1cm} (3.12)

where, \( x \) = independent variable, \( y \) = dependent variable, \( \text{cov}(x, y) \) = covariance of \( x \) and \( y \), \( \sigma_x \) = standard deviation of variable \( x \), \( \sigma_y \) = standard deviation of variable \( y \)

The value of ‘\( r \)’ may vary between +1 and -1. Perfect positive correlation and a negative correlation exists when \( r = +1 \) (the two variables increase each other) and when \( r = -1 \) (one decreases while the other increases). No correlation exists when \( r = 0 \). A strong correlation exists when \( r > \pm 0.5 \). A moderate degree of correlation exists when \( r \) is between \( \pm 0.3 \) and \( \pm 0.5 \). Possibly less correlation exists when \( \pm 0.1 \leq r < \pm 0.3 \). Thus, the two variables \( x \) and \( y \) are highly correlated if the correlation coefficient ‘\( r \)’ has a larger value.

3.3.2 Regression Analysis

It is a statistical tool used to estimate the value of unknown variables from a known value of another variable. The regression analysis helps to find out the influence of one variable to increase or decrease the value of another variable (Patricia Cohen et al. 1983). It includes many techniques for modeling and analyzing several variables and determine the direction of relationship between a dependent variable and one or more independent variables (or 'predictors'). More specifically, regression analysis helps one to understand how the typical value of the dependent variable (or
'criterion variable') changes when any one of the independent variables is varied, while the other independent variables are held fixed. There are two regression equations, the equation of 'X' on 'Y' describes the change in the values of 'X' for a given change in 'Y', and the regression equation of 'Y' on 'X' express the variation in the values of Y for a given change in X. The forms of the regression equation are usually bi-variate or multi-variate. The analyst must choose based on how many functions and variables can influence the relation between them. The most frequently used linear model relates a dependent variable ‘Y’ to a single independent variable ‘X’ and represented in Equation (3.13).

$$Y = b_0 + b_1X + \varepsilon$$  \hspace{1cm} (3.13)

where, $b_0$ is Intercept Coefficient, $b_1$ is Slope Coefficient and $\varepsilon$ is Error term. The Intercept Coefficient $b_0$ represents the value of dependent variable ‘Y’ when the value of independent variable ‘X’ equals zero. The slope coefficient $b_1$ represents the rate of variation in the value of dependent variable ‘Y’ on the change in the value of independent variable ‘X’.

### 3.3.2.1 Multivariate regression analysis

A simple regression analysis estimates the linear relationship between a dependent variable 'Y' and an independent variable 'X', whereas to find the association between a dependent variable 'Y' and more than two independent variable X (X1, X2, ..., Xn) require multiple regression analysis.

MVA (Multivariate Analysis) model is a combination of multiple linear regression analysis and simple linear regression analysis (Patricia Cohen et al. 1983). The multi-variable statistical model contains multiple variables on the right side of the model equation and estimate the linear
association between the dependent variable $Y$ and independent variables $X$. A simple linear regression model has a continuous outcome and one predictor, whereas a multiple or multivariable linear regression model has a continuous outcome and multiple predictors (continuous or categorical). The dependent variable $Y$ can be continuous or categorical or a mixture of both. The relationship between the two variables is expressed in Equation (3.14)

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k$$  \hspace{1cm} (3.14)

where, $Y$ - dependent or Response variable, $X$ - independent or Predictor variable, $\beta$ - Coefficient, (calculated using least square estimation). The Equation (3.14) can be represented as a matrix and is shown in Equation (3.15)

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} 1 & X_{11} & X_{12} & \cdots & X_{1k} \\ 1 & X_{21} & X_{22} & \cdots & X_{2k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X_{n1} & X_{n2} & \cdots & X_{nk} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_n \end{pmatrix}$$  \hspace{1cm} (3.15)

Correlation coefficient $\beta_0$ to $\beta_n$ are used to analyze the linear relationship between the predicted and measured variables.

### 3.4 PROPOSED WORK

The proposed model assumes a non-clustering mechanism that leads to a network more flexible regarding new nodes connecting to the network. The ZigBee protocol on top of IEEE 802.15.4 nodes is designed using hexagon with center node topology for simulation analysis. The network abstracts three layers (application layer, data link layer and physical layer) as cross-layer besides the action of the network.
Figure 3.1 Flowchart for cross-layer analysis of QoS under statistical methods

The intellectual flowchart of the proposed model is detailed in Figure 3.1. First, the parameters of the physical layer (transmission power, RSSI and energy threshold indicators) are fine-tuned to $-\text{value}$ to $+\text{value}$ in WSN layer parameters as predictor variables $(X)$. Select different samples $(X)$ and collect Metrics $(Y)$ using Qualnet simulation.

To qualify or quantify? To qualify relationship

To quantify relationship

Perform Univariate regression analysis

Perform Multivariate regression analysis

Construct MVA model using SPSS S/W

Categorize strong and weak correlation

Perform residual analysis

Find the impact of $X$ on $Y$ variable

Validate the model

Tune and find trade-off between cross-layer parameters

Stop

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Construct MVA model using SPSS S/W

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Perform residual analysis

Find the impact of $X$ on $Y$ variable

Validate the model

Tune and find trade-off between cross-layer parameters

Stop
the units of dB and the samples are collected on specified QoS. Then, the MAC layer parameters SO, BO, MinBE and MaxBE are fine-tuned from min to max value, and the samples are collected on specified QoS. Finally, the size of the packets in the application layer is varied to adjust the traffic in the network and the samples are levied on specified QoS. All these three layer parameters are taken as the independent variables (predictor), and the observed QoS values from the Qualnet simulation are used as the dependent variables (response) in the Multivariate Regression Analysis Model.

3.4.1 Correlation-Aware QoS Analysis

The statistical relationship between the WSN protocol stack parameters and QoS was examined, through the analysis of the linear correlation method. Correlation most often refers a linear relationship between two variables. The correlation coefficient ‘r’ between two parameters x and y is determined. The positive correlation value represents that the increase in the value of one variable is related to a comparable increase in the value of another variable. Tables 3.1 and 3.2 lists the correlation results for the collected simulation samples. Correlation predicts the relationship between variables that can be exploited in practice. According to the guidelines, the correlation is good if $r \geq 0.5$, and marginal, if $0.1 < r < 0.5$. Table 3.1 indicates that transmission power is strongly correlated with energy, throughput, and SNR but finds low correlation for the delay. Similarly BO, SO shows low correlation for energy and highly correlation for the delay. The PS is strongly correlated for SNR, but finds less correlation for throughput. ET is strongly correlated for energy and throughput but has low correlation for the delay. Conversely, the RSSI shows no correlation for SNR but strongly correlated for throughput. Hence it was difficult to attain trade-off between QoS as one parameter favors one QoS and at the same time reflects adverse effect with another QoS. Therefore, it is necessary to understand the
positive and the negative correlation among QoS metrics. The correlation analysis model is built from obtained sample values of 100 nodes, 50 nodes and 25 nodes for energy, delay, throughput, and SNR. The obtained correlation matrix of Table 3.2 from the correlation analysis model implies that energy is negatively correlated with delay, but positively correlated with SNR. Similarly, throughput is positively correlated with the delay but negatively correlated with energy and SNR. Based on the correlation matrix and QoS performance matrix it is necessary to study the influence of more than one variable to bring trade-off to overcome the conflict among QoS.

**Table 3.1 Correlation analysis of AMP parameters in WSN**

<table>
<thead>
<tr>
<th>Correlation value</th>
<th>Correlation levels</th>
<th>QoS Performance Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Energy</td>
</tr>
<tr>
<td>0 to 0.1</td>
<td>low Correlation</td>
<td>BO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SO</td>
</tr>
<tr>
<td>0.15 to 0.5</td>
<td>Moderate correlation</td>
<td>MinBE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MaxBE</td>
</tr>
<tr>
<td>0.5 to 1</td>
<td>Strong correlation</td>
<td>ET</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TP</td>
</tr>
</tbody>
</table>

**Table 3.2 Correlation matrix of QoS metrics**

<table>
<thead>
<tr>
<th>QoS Performance Metrics</th>
<th>Parameter</th>
<th>EC</th>
<th>TP</th>
<th>AD</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>-0.126</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>-0.564</td>
<td>0.037</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SNR</td>
<td>0.377</td>
<td>-0.249</td>
<td>-0.055</td>
<td>1</td>
</tr>
</tbody>
</table>
3.4.2 Cross-layer Analysis of QoS Metrics using Multiple Regression Frameworks

The statistical multiple regression analysis has been used to understand the correlation between the AMP parameters (independent variables) and a QoS metric (dependent variable). The observations of a Wireless sensor network for 100 nodes, 50 nodes and 25 nodes of hexagon topology are collected by varying the values of selected independent variables (transmission power, RSSI, energy threshold, SO, BO, MinBE, MaxBE & PS) of WSN layer from low to high range. The obtained dependent variable (QoS such as Energy, delay, SNR and throughput) with the different value of different AMP parameters were used as input data to the multiple linear prediction models.

Table 3.3 Regression analysis table

<table>
<thead>
<tr>
<th>S.No</th>
<th>Regression Equations</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$EC=0.00352-0.00022×ET-0.000022×TP-0.000000349×BO+0.000303×SO-0.000153×MinBE+0.000032×MaxBE-0.000075×PS+0.000062×RSSI$</td>
<td>0.9731</td>
</tr>
<tr>
<td>2</td>
<td>$AD=-20.8+0.094×ET+0.0088×TP+2.07×BO-1.13×SO+1.00×MinBE-0.23×MaxBE+0.42×PS-0.48×RSSI$</td>
<td>0.6031</td>
</tr>
<tr>
<td>3</td>
<td>$T=-89.32-0.566×ET+0.7375×TP+5.2628×BO-4.037×SO+2.4858×MinBE+0.2988×MaxBE+0.6418×PS-2.5607×RSSI$</td>
<td>0.9999</td>
</tr>
<tr>
<td>4</td>
<td>$SNR=310-0.107×ET-4.923×TP+81.1×BO-29.1×SO-67.2×MinBE+8.71×MaxBE-6.30×PS-9.47×RSSI$</td>
<td>0.9972</td>
</tr>
</tbody>
</table>

A multi-linear regression analysis was carried out, using the IBM SPSS (Statistical Package for Social Science) software. Table 3.3 represents the obtained QoS Regression equation of the multivariate model. In Table 3.3, EC is Energy Consumption, AD is Average Delay, T is throughput and SNR is Signal to Noise Ratio. The estimated $R^2$ value of this model ($R^2 > 0.9$) indicates that the chosen parameters are significantly correlated with the
chosen QoS. Whereas, the $R^2$ value of delay is greater than 0.5 but lesser than 0.9 stating that certain other factors need to be considered. This is further analyzed in the results sections.

3.5 RESULTS AND DISCUSSION

In the following section the performance evaluation of statistical models under varied values of AMP parameters is performed. Based on the outcome of the prediction model the AMP parameters were tuned to obtain balance among QoS.

3.5.1 Network Set-up

The network assumes that the sensing region is a 2D space, sized 1500 X 1500 meters. The devices or the sensor nodes deployed were all stationary nodes in the area of terrain in Qualnet. The WSN is represented as an undirected graph $G (S, L)$, where $S$ denotes the set of sensor nodes and $L$ denotes a set of wireless links between the sensors. The network model uses IEEE 802.15.4 over WPAN under hexagon topology with the center node of network size 100. Each sensor node contains an internal power source to support its sensing and communication activities. The initial energy of node $N_i$ is assumed to be $E_i$ (Joules). PHY-MAC layer based ZigBee contains transmission power, RSSI, Energy detection threshold, beacon order, superframe order, MACminBE and MACmaxBE parameters. IEEE 802.15.4 works as reduced function device, while the devices are most likely to be the battery powered and low data rate. The nodes broadcast beacon periodically to establish the network connection. In the beacon-enabled mode, 802.15.4 uses slotted CSMA-CA for channel access and contended for the utilization of the channels. All of the sources in this network send the data to sink node. Then, CBR traffic with packet size of 10 second periods has been allocated.

The battery model is chosen as linear for 60 seconds with full battery capacity charge of 1200 units. The energy model of ZigBee is MICA
motes. In this simulation, values of TP, RSSI & ET of physical layers are varied from -32 to +32 dB for TP, -95 to +95 dB for ET by adjusting temperature power and noise factor for RSSI. The SO and the BO of MAC layer parameters varied from 0 to 14 bps. The MinBE and MaxBE of MAC layer parameters ranged from 0 to 3 and 4 to 8 bps. The PS parameter of application layer varied with the data rate ranging from 0 to 150 bps.

3.5.2 Performance Evaluation of Cross-layer Framework

The QoS parameters were analyzed based on the tuned AMP parameters using the multivariate regression analysis model. This model is more suitable for analyzing more than one AMP parameter and determines the best AMP correlated parameters on QoS. The obtained results for various AMP parameters are shown in Figures 3.2 to 3.6. Figure 3.2 depicts the correlation analysis of QoS metrics with respect to individual AMP parameters. From Figure 3.2 it is known that the transmission power is highly correlated with energy of about 45% and 25% with SNR. Therefore the energy consumption can be controlled by tuning the transmission power to the appropriate value. However, from the QoS correlation matrix the delay seems to increase when the energy consumption is decreased since energy and delay are negatively correlated. Similarly, the RSSI is strongly correlated for throughput of about 30% and the SO happens to be a more correlated parameter for average delay of about 36%. The delay can be reduced by controlling the SO parameter but at the same time throughput may decrease according to the QoS performance metrics of Table 3.1. From the analysis it is clear that the individual parameter can favour and balance at the maximum of two QoS metrics. Therefore to attain balance among more than two QoS metrics require the combination of parameters and hence require the analysis of the cross-layered behavior of parameters. This can be done using the obtained prediction model by substituting the determined value of required
parameters and substituting the zero value to the suppressed parameters in the equation. The obtained prediction model is represented in Table 3.2.

![Image of Figure 3.2: Analysis of individual AMP parameter versus QoS metrics](image1)

**Figure 3.2** Analysis of individual AMP parameter versus QoS metrics

![Image of Figure 3.3: Analysis of ET with MAC and application layer parameters versus QoS metrics](image2)

**Figure 3.3** Analysis of ET with MAC and application layer parameters versus QoS metrics
Figure 3.4 Analysis of TP with MAC and application layer parameter versus QoS metrics

Figure 3.5 Analysis of RSSI with MAC and application layer parameter versus QoS metrics
The cross-layer behavior among the physical, MAC and application parameters results were shown from Figures 3.3 to 3.6. First each physical parameter with MAC layer and Application layer parameter is analyzed and the results were shown from Figures 3.3 to 3.5. Figure 3.3 represents the influence of the energy threshold parameter with other MAC and application layer parameters with respect to QoS. From the Figure 3.3, the energy threshold (physical layer) and packet size (application layer) are considered for highly correlated parameters (72 %) in power consumption specific applications. ET and MinBE show 14 % correlation for throughput. ET and SO shows 38 % correlation for the average delay. In Figure 3.4, the transmission power of physical parameter and other MAC and application layer parameters are analyzed. The TP and PS show 59 % correlation for energy consumption. Similarly, the correlation result of Figure 3.4 shows 38% correlation for TP and SO, 20 % for TP and BO, 38 % for TP and PS with respect to delay, throughput and SNR respectively. In Figure 3.5, the RSSI of the physical parameter and other MAC and application layer parameters are analyzed. The RSSI and PS shows 15% correlation for energy
consumption & RSSI and BO shows 18% correlation for throughput. Similarly, RSSI and SO shows 42% for the average delay, RSSI and PS parameters shows 16% for SNR. From Figures 3.2 to 3.5 it is understandable that balance among QoS is improved with cross-layer framework. Similarly, from Figure 3.6, it is very much known that MAC parameters play a vital role in energy, delay and SNR when compared with physical parameters. Conversely, physical parameters play a crucial role for throughput when compared with MAC parameters.

![Figure 3.7 Comparison of measured and predicted energy consumption](image_url)

![Figure 3.8 Comparison of measured and predicted average delay](image_url)
Figure 3.9 Comparison of measured and predicted SNR

![Figure 3.9](image1.png)

Figure 3.10 Comparison of measured and predicted throughput

![Figure 3.10](image2.png)
Hence, from the analysis of Figures 3.2 to 3.6 it is noted that an appropriate physical and a particular MAC parameter need to be chosen and properly tuned to attain trade-off between energy, delay, throughput and SNR. Prediction analysis using the multivariate regression model is compared with observed measures and the results are shown from Figures 3.7 to 3.10. From Figures 3.7 to 3.10 it is clear that the observed values lie linear to the predicted values and hence the prediction model is reliable to maximize or minimize the equation results.

3.5.3 Correlation-aware tuned AMP Parameters to Balance QoS Metrics

The correlation analysis model and MVA model result analysis determines TP, SO, RSSI and PS are best AMP parameter combination to attain better trade-off among QoS. Figures 3.11 to 3.14 shows the results of tuned AMP parameters based on the analysis from Figures 3.2 to 3.10. The values of X1 to X7 of x-axis parameters of Figures 3.11 to 3.14 are X1 as TP=1 MinBE=2 RSSI=-75 PS=120, X2 as TP=2 MinBE=3 RSSI=-75 PS=85, X3 as TP=1 MaxBE=7 RSSI=82 PS=75, X4 as TP=2 MaxBE=8 RSSI=-82 PS=65, X5 as TP=2 SO=11 RSSI=-95 PS=45, X6 as TP=1 SO=2 RSSI=-95 PS=55 and X7 as TP=1 SO=11 RSSI=-95 PS=45. In Figure 3.11, the energy consumption is reduced by considering TP=1, SO=2, RSSI= -95, PS=55 but at the same time the delay is increased and it is depicted in Figure 3.12 for the X6. This is true according to the analysis of correlation matrix Table 3.2 where it is analyzed that energy and delay are negatively correlated. From the analysis of Figure 3.2 to 3.6, it is evident that a better combination is needed to control delay.
Figure 3.11 Energy consumption analysis

Figure 3.12 Average delay analysis
Similarly, Figure 3.14 shows better throughput for the considered above parameter values and at the same time SNR is also increased and it is depicted in Figure 3.13 for the X6. This is also true according to the analysis of correlation matrix Table 3.2 where it is analyzed that throughput and SNR are positively correlated stating that increase of one parameter influence the increase of another parameter. From the analysis of Figures 3.2 to 3.6, a better
value is assigned to the SNR correlated parameter to achieve better trade-off with throughput. Based on the prediction and correlation analysis, the parameter values are needed to be reassigned correctly. Moreover, a trade-off between throughput, SNR, energy and delay can be achieved by properly tuning the respective correlated parameters based on the results of obtained correlation matrix and prediction model. Furthermore, the properly tuned values for the best-correlated parameters on QoS are depicted for the value X7 from Figures 3.11 to 3.14 by considering TP=1, SO=11, RSSI=-95, PS=45. Thus, the best trade-off is attained between Energy, delay, throughput and SNR in respect of their +ve and –ve correlation between them by tuning the respective correlated AMP parameters and by varying the values from low to high or vice versa.

3.6 CONCLUSION

This chapter presented the correlation and regression analysis of the physical, MAC, and application layer parameters to attain balance among QoS. The obtained multivariate regression model predicts the best AMP correlated parameters for the selected QoS. The obtained predictors using multivariate and correlation analysis model was validated under simulation. The simulation result shows that TP, SO, RSSI and PS are the strongly correlated parameters for energy, throughput, delay and SNR. Further, the analysis concludes that the prediction provides insights to improve throughput, SNR and energy through combination of appropriate QoS correlated WSN layer parameters and tune their value to meet the application requirements within resource availability constraints. Whereas, to reduce delay require a robust dynamic communication protocol that adapts dynamically with diverse application to ensure balance among conflict QoS.