# A Stack Cross-layer Analytical Model for CSMA/CA IEEE 802.15.4 Networks

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## ABSTRACT

Because of the specifications in low-cost, low-power IEEE 802.15.4 wireless sensor networks, comprehensive analytical model is important for evaluating performance under varying wireless channel constraints. The systematic properties of single physical layer and medium access control (MAC) layer protocol have been studied through the techniques based on mathematical models or experiment-based approaches. However, It is insufficient to evaluate network performance on the basis of existing single layer model or cross-layer model with stationary parameters, especially for the multi-variable parameters-based wireless network environment. In this paper, we propose an enhanced stack cross-layer analytical model based on the comprehensive combination and interaction between PHY layer propagation model and MAC layer Markov chain model. Dynamic interaction between sub-layer models achieve adaptive performance estimation with hyperparameters sets. Cross-layer performance degradation is analyzed under the varying inputs of multi-parameters vectors, several Quality of Service (QoS) metrics and effective energy consumption metric are proposed and evaluated, respectively. From the simulation results compared with benchmark models, stack cross-layer model offers more comprehensive performance analysis with different cross-layer parameters sets which include distance, transmit power, noise power, and information loads, etc.

## KEYWORDS

wireless sensor network, IEEE 802.15.4, cross-layer model, multivariate parameters

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## 1 INTRODUCTION

Due to the different applications and environment constraints in wireless sensor network, performance analytical model is important study for the evaluation and estimation on Quality of Service (QoS) and energy consumption. Apart from empirical-based approach, several studies [2, 4, 5, 8, 11] focus on the analytical model based on the Markov chain model. Analytical studies aim to develop generalized mechanisms with multivariable functions which is able to track network performance with key indicators (such as throughput, reliability, delay, etc.). In the existing methods of cross-layer analytical model [2, 8, 11], performance metrics of each sub-layer are calculated independently. Joint model [11] consider additional influence of physical channel constraints, which is combined with Markov MAC layer model in order to reproduce synthetic performance analysis. However, joint model [11] only calculate a constant value of packet reception rate in PHY layer model where interpreted into Markov chain model of CSMA/CA mechanism. Due to the uncertainty features in WSNs, different application schedules and varying parameters generate fluctuating performance degradation. Performance analysis should be considered under the sets of multivariate hyperparameter. In this paper, we propose a dynamic stack cross-layer analytical model based on IEEE 802.15.4 CSMA/CA mechanism which combined PHY layer propagation model and MAC layer Markov chain model in a sufficient way. The interactional PHY and MAC layer models share multi-dimensional systematic parameters from multivariate input vectors (include information load, transmit distance, transmit power, SNR, etc.). Cross-layer overhead increases along with the changing values of parameters input space, which cause the packet transmission error on physical channel. Dynamic PHY channel constraints impact on CSMA/CA mechanism will result in further global performance degradation. Besides, we propose an energy consumption evaluation metric based on instantaneous QoS. Effective energy consumption represents the expected energy expenditure for each successfully transmitted bit, which indicates the overall energy conversion efficiency.

The remainder of this paper is organized as follows. Section II represents related researches that offer the fundamental structure and inspire our work. In section III, our stack cross-layer analytical model is proposed and discussed in detail. Section IV represents simulation scenario and performace evaluation results of stack model which are compared with benchmark model. Finally, Section V concludes this paper and discusses potential improvement in future work.

## 2 RELATED WORK

Some related researches try to reproduce IEEE 802.15.4 standard performance and achieve further optimization mechanism. This paper is inspired by several existing researches and parts of related works are introduced as follows. On the one hand, Markov chain model is frequently used in the systematic performance analysis on CSMA/CA MAC layer protocol. [5] firstly propose Markov-based analytical model which mimic the performance of slotted CSMA/CA mechanism. The generalized analysis allows to measure reliability, delay and energy consumption by a Markov chain, depending on the collision probability in unsaturated traffic network. [4] analyses the performance of CSMA/CA mechanism in non-ACK mode by modified Markov chain model. In [1], authors provides analytical model through event chains computation approach. It only considers chains with a probability to occur greater than pre-defined threshold to reduce complexity. Markov model with $k$ states is proposed in [8] to account for varying changing conditions under LR-WPAN lossy channel, error rate and frame sequences correlation are derived between transmitter and receiver. On the other hand, several studies focus on PHY layer model in order to reproduce the performance influence of physical channel constraints. [10] quantifies the impact of PHY channel constraints and hardware variance on unreliable and asymmetric link, generate expectation and variance of packet reception rate through given transmission region boundary. PHY layer transmission model [3] is built based on the degradation of AWGN channel and block Rayleigh fading channel. Expected energy cost for each successfully received bit is considered as metrics for energy consumption analysis. Numerical parameters about transmission power, transmit hoping distance with different modulation scheme are optimized in order to find the energy consumption minimization of packet transmission.

Besides, several works make the combination of sub-layer models aim to faithfully mimic the cross-layer functionalities. [2] proposes a cross-layer model based on the integrated MAC and PHY layer models, which consider the impact of multi-path shadow fading channels on network performance. A joint layer model is presented in [11], which make the combination of two relevant models from PHY and MAC layer. Transmission error on PHY layer is calculated then additional estimation is integrated into Markov MAC layer model. However, The PHY layer model only consider transmission error as a static estimation value from independent computation. How to develop cross-layer dynamic tuning model with multivariable distribution function is the object of improvement.

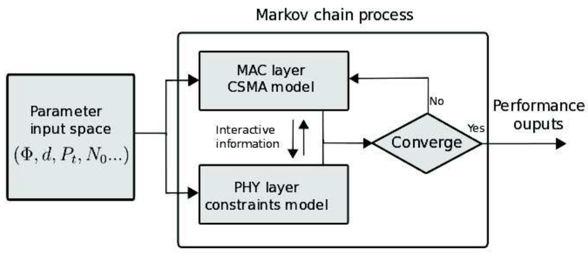



**Figure 1: stack cross-layer model structure**

## 3 STACK CROSS-LAYER IEEE 802.15.4 MODEL

Our research is based on [11] which proposed analytical joint model over PHY and MAC layer. It combined two relevant models together, by considering with the impact of PHY layer error on Markov chain model based on MAC layer, in order to elaborate the performance description. However, the PHY layer model did not consider environment parameters as variables, output of PHY layer packet transmission error probability is computed as a static value to be joined into MAC layer model along with the different information load. Thus, we propose a stack cross-layer IEEE 802.15.4 analytical model aims to integrate channel parameters variables into submodel of each layer to obtain more precise performance estimation and more widely performance evaluation in different states of sensor network environment .

The structure of stack model workflow is illustrated in Figure 1. Only information load $\Phi$ is considered as variable input in joint model. On the basis of that, more variables are considered as input parameter sets of performance analysis in stack model, such as propagation distance $d$, transmit power $P_t$ and noise power $N_0$, etc. The multi-interactions between submodels generate the combined performance analysis model to obtain dynamic performance response in the case of network environment with multivariable parameters. Simulation process follows M/M/1/K queueing model [11] as convergence control mechanism.

For the MAC layer model, we adapted the Markov chain model from [5]. Three elemental variables in CSMA/CA procedure are defined by $\tau$, $\alpha$ and $\beta$. They denote three states probability in channel clear assessment (CCA) procedure, which indicate the probability when node is not in idle state in a random slot, the first CCA attempt failure probability and the second CCA attempt failure probability respectively. Following the expressions in [5], the system error can be estimated as follows:

$$x = \alpha + (1 - \alpha)\beta \tag{1}$$

$$y = (1 - (1 - p_{c,f})(1 - p_{e,f}))(1 - x^{N_{caf}+1}) \tag{2}$$

$$p_{caf} = \frac{x^{N_{caf}+1}(1 - y^{N_{rtx}+1})}{1 - y} \tag{3}$$

$$p_{rtx} = y^{N_{rtx}+1} \tag{4}$$

Where, $x$, $y$ represent probability of CCA attempts failure and transmission failure in the range of maximum CCA attempts limitation $N_{caf}$ respectively. $p_{caf}$, $p_{rtx}$ denote the probability of packet discard due to maximum CCA attempts limitation and maximum retransmissions failure attempts respectively.

Additionally, we analyse the transmission failure probability due to PHY layer channel constraints. The physical layer transmission model is developed based on the approaches from [3, 9, 10]. Propagation distance, transmit power, fixed circuit energy consumption and symbol/packet error are included as variables of PHY layer model based on Additive White Gaussian Noise (AWGN) channel. Typical symbol error based on different modulation can be derived from formula table [7], we only consider BPSK modulation in this paper. After substituting the physical parameters into expression, eventually, symbol error probability $p_{e,s}(BPSK)$ is expanded as follow:

$$p_{e,s|BPSK} = Q\left(\sqrt{\frac{P_t G_T G_R \Phi^2}{(4\pi)^2 d^2 B N_0}}\right) \tag{5}$$

Where symbol error probability with BPSK modulation is computed approximately with Q-function. $({}^{4\pi d}/_{\Phi})^2$ is defined as free-space path loss factor with propagation distance $d$, $G_T$ and $G_R$ denote the antenna gain of transceiver. It can be deduced that transmission power $p_t$ provides positive correlation with $p_{e,s}$. Transmission distance $d$, bit repetition rate $\phi$ and noise power $N_0$ with bandwidth $B$ are in negative correlation with $p_{e,s}$. Additionally, packet transmission failure can be represented in Rayleigh fading channels as follow:

$$p_{e,f} = 1 - (1 - p_{e,r}(\gamma < \gamma_t))(1 - p_{e,s})^{n_s} \tag{6}$$

where $p_{e,r}$ indicates average transmission error probability due to system outage over Rayleigh fading channels, the number of symbols per packet is defined as $n_s = (L_P - L_H)/log_2(M)$ in the condition of packet with $L_P$ bit payload size. Therefore, packet transmission error probability is computed which undergo different physical channel constraints with varying parametric variables set. This can allow us to integrate PHY layer performance degradation adaptively into MAC layer model in order to obtain stack model with extensional parameters.

System delay is considered as the expected time expenditure to transmit a packet successfully. Expected number of retransmissions attempts $\mathbb{E}[n_{rtx}]$ is defined in Equation 7 to evaluate the influence of variable parameters on time overhead for receiving packet. $P(X = n)$ represents probability

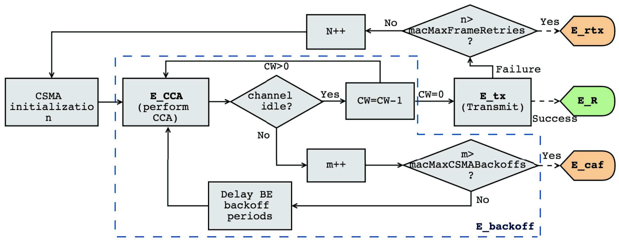



**Figure 2: Effective energy consumption in CSMA/CA mechanism**

corresponding to each number of retransmission attempts, $N_{rtx}$ is maximum retransmission attempts limitation. After expanding expression, $\mathbb{E}[n_{rtx}]$ could be described with $p_{c,f}$ and $p_{e,f}$. Furthermore, the total expectation value of time overhead $\mathbb{E}[\tau_d]$ is expressed in Equation 8. $\mathbb{E}[\tau_0]$ represents the time consumption of a successfully transmission, wasted time overhead can be divided into the summation of each expected time intervals multiplied by the corresponding number of retransmissions attempts respectively.

$$\mathbb{E}[n_{rtx}] = \sum_{n=1}^{N_{rtx}-1} \tau_n P(X = n) \tag{7}$$

$$= \frac{(1 - (1 - p_{c,f})(1 - p_{e,f}))(1 - (1 - (1 - p_{c,f})(1 - p_{e,f}))^{N_{rtx}})}{(1 - p_{c,f})(1 - p_{e,f})}$$

$$\mathbb{E}[\tau_d] = \mathbb{E}[\tau_0] + \mathbb{E}[n_{rtx}](T_{DATA} + T_{ACK}^{timeout} + 2T_{IPS}) + \frac{\mathbb{E}[n_{rtx}]}{N_{rtx} - 1} \sum_{n=1}^{N_{rtx}-1} \mathbb{E}[T_{backoff}(n)] \tag{8}$$

Cross-layer energy consumption analytical model is proposed based on the combination of PHY layer and MAC layer energy analytical model. Overall energy consumption is separated into effective energy consumption and wasted energy expenditure, as illustrated in Figure 2. In the basic procedure of CSMA/CA mechanism, Clear Channel Assessment is excuted in contention window size, backoff mechanism reset CCA procedure in the case of congestion. Frequent channel congestions increase the dependent energy usage on backoff mechanism for each successful packet transmission. Therefore, packet discard due to maximum backoff failure numbers or maximum frame retries attempts limitation result in the wasted energy without successfully data transmission. The effective energy consumption can be estimated with expectation of energy consumption for receiving every bit information successfully, which is accepted as metrics to demonstrate the efficiency of energy conversion in given network environment parameters. As presented in Equation 9-13, each part of expected energy consumption value could be computed separately:

$$\mathbb{E}[E_{backoff}] = \sum_{i=0}^{n_{caf}} (\alpha - (1-\alpha)\beta)^i \left(2 + \frac{\alpha + 2(1-\alpha)\beta}{\alpha + (1-\alpha)\beta} i\right) \cdot (E_{CCA} + E_{c,fixed}) \quad (9)$$

$$\mathbb{E}[E_{caf}] = \sum_{j=1}^{n_{caf}} y^j j (E_{backoff} + E_{tx} + E_{c,fixed}) + (n_{rtx} + 1) \frac{\alpha + 2(1-\alpha)\beta}{\alpha + (1-\alpha)\beta} (E_{CCA} + E_{c,fixed}) \quad (10)$$

$$\mathbb{E}[E_{rtx}] = (n_{rtx} + 1)(E_{backoff} + E_{tx} + E_{c,fixed}) \quad (11)$$

$$\mathbb{E}[E_R] = \sum_{j=0}^{n_{caf}} y^j (j+1)(E_{backoff} + E_{tx} + E_{c,fixed}) \quad (12)$$

$$E^* = \frac{R^* \cdot E_R + p_{caf} E_{caf} + p_{rtx} E_{rtx} + p_{idle} E_{idle}}{R^* \cdot \Phi(L_p - L_H)} \quad (13)$$

Where overall energy consumption is separated into several aspects. $\mathbb{E}[E_R]$ represents the energy expenditure in terms of reliable transmission. $\mathbb{E}[E_{backoff}]$ indicates the elementary energy that sensor node performs backoff procedure in the CSMA/CA backoff mechanism. $\mathbb{E}[E_{caf}]$, $\mathbb{E}[E_{rtx}]$ are calculated for the expected wasted energy in failed CSMA/CA procedure due to channel access failure and maximum number retransmission attempts, respectively. $E_{c,fixed}$ is fixed circuit energy of transmitter and receiver [9]. Consequently, the overall efficiency of energy consumption is derived from Equation 13. The summation of expected energy overhead $E^*$ is computed depend on the prior probability of each state then divided by reliable throughput in bit.

## 4 SIMULATION AND RESULTS

We analyze simulation results of stack cross-layer analytical model through the comparison with benchmark models in different simulation scenarios. The simulation concludes two aspects of performance evaluation. On the one hand, the relationship between system performance degradation and input variables is evaluated. Information loads $\Phi$ and propagation distance $d$ are selected as two scenarios in the experiment. On the other hand, four metrics (Thoughtput, Delay, Reliability and Effective energy consumption) are chosen to characterize node performance with increasing information loads. Besides, we evaluate the effective energy consumption by stack model which is under multi-dimensional parameters space. Joint model [11] and typical MAC layer model [5] are evaluated as benchmark performance. The elementary power states [6] and CSMA/CA parameters are listed in Table 1.

### 4.1 Analysis of packet error probability with multivariable parameters

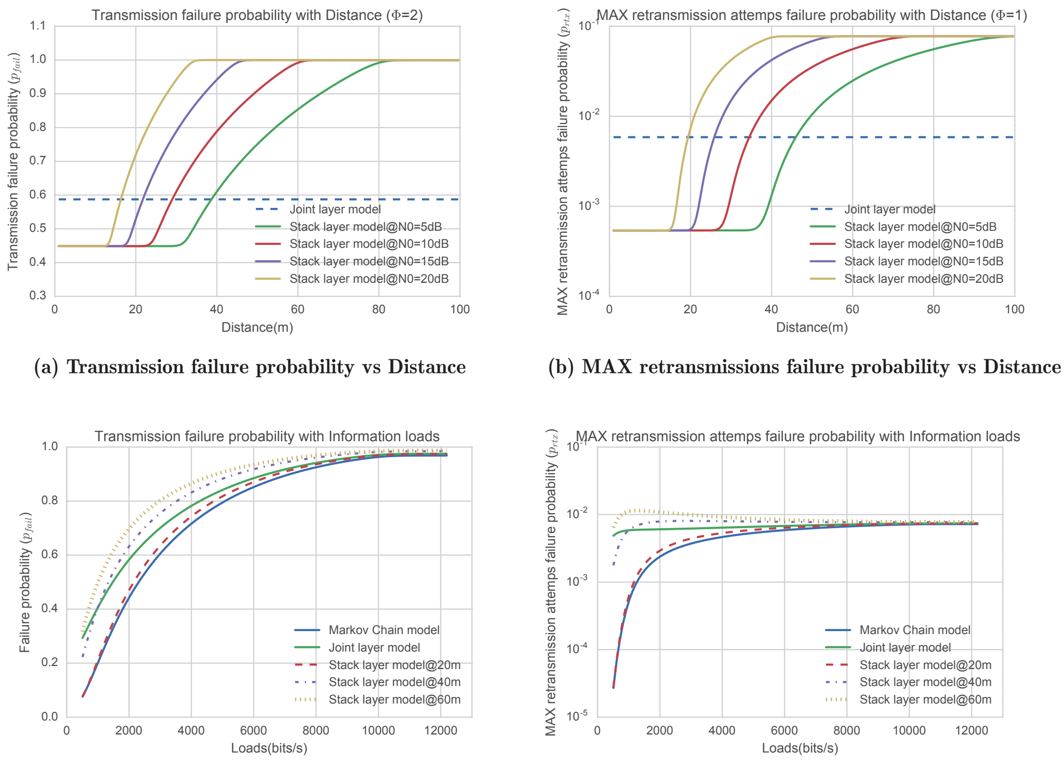
Firstly, we characterize packet error probability over distance variable. In Figure 3a, transmission failure probability of stack model is simulated in the range of transmission distance parameter from 0 to 100 m in channel environment with different noise power. The information load $\Phi$ is given at 2 frame/s. According to the description of joint cross-layer model, dashed line represents the static estimated output of transmission failure probability in 20 m distance range. In stack model, transmission failure is counted dynamically through the combination of PHY and MAC layer model. Under the case that noise power $N_0$ = 10 dB, transmission failure probability increases significantly during the distance range 20 to 60 m. Thus, theoretical transmission distance can be predicted from given parameters. It can be observed that higher channel noise level increases the probability of packet transmission error in given distance. Figure 3b demonstrates packet discard probability due to the maximum retransmission attempts failure of CSMA/CA procedure. Prior probability of combined transmission failure boosts probability distribution variance of maximum packet retries limitation in different distances and noise levels. Furthermore, Figure 3c compares performance degradation on transmission failure under three transmission distances. Joint model generates significant impact on transmission failure probability, which is compared to single MAC layer model, especially in the light information loads. Constant output of PHY channel error have risk of overestimation for the condition of multivariate parameters. From the results in different distances, it is obvious that expanded information loads $\Phi$ results in frequent channel collision $p_{c,f}$ and maximum CSMA backoff failure $p_{caf}$ which is under PHY channel constraints $p_{e,f}$. It further causes a higher probability of failed packet transmission. Transmission failure probability also presents growth trend with increasing distance parameter simultaneously in each parts of simulation scenario $\Phi$, which verifies the output in Figure 3a. Similar analysis can be interpreted to the performance variance of maximum retransmissions failure probability, as shown in Figure 3d.

**Table 1: Simulation Parameters**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Node numbers | 10 | $L_H$ | 6 *bytes* |
| MacMinBE | 3 | $L_P$ | 127 *bytes* |
| MacMaxBE | 5 | $E_{tx}$ | 30 $mW$ |
| MacMaxCSMABackoffs | 4 | $E_{rx}$ | 40 $mW$ |
| MacMaxFrameRetries | 3 | $E_{CCA}$ | 40 $mW$ |
| MinBackoffExponent | 3 | $E_{idle}$ | 0.8 $mW$ |
| MaxBackoffExponent | 5 | $\overline{E}_{c,fixed}$ | 2.86 $\mu J/S$ |

### 4.2 Comparison between stack layer model and joint layer model

In this subsection, we compare the global performances of stack model, joint model and single MAC layer model which are appraised under pressure testing scenario. Data information load $\Phi$ increases from 400 bits/s to 12000 bits/s with given parameters sets. As shown in Figure 5a, with low data loads, adaptive PHY layer model provides inconspicuous influence on node average thoughtput. Under the case of stable condition, stack model keeps cautious estimation on PHY




**(a) Transmission failure probability vs Distance**

**(b) MAX retransmissions failure probability vs Distance**

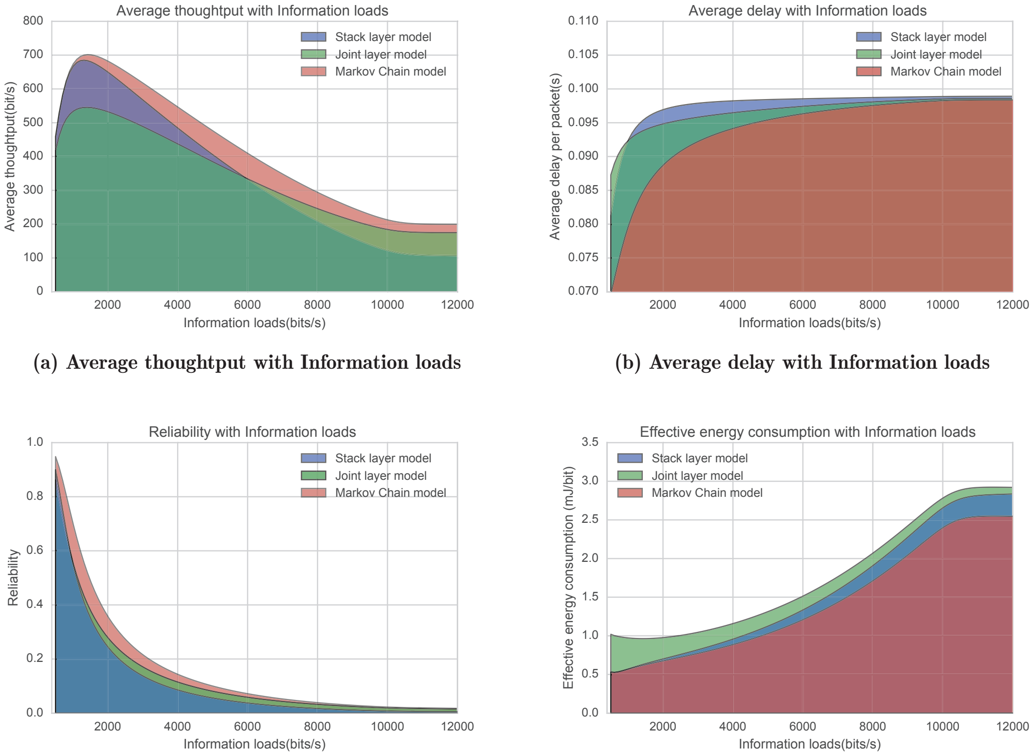
**(c) Transmission failure probability vs Information loads**

**(d) MAX retransmissions failure probability vs Information loads**

**Figure 3: Comparison between Stack cross-layer model and benchmark model in different scenarios**

channel error which compared with joint model. As offered information loads increase to the saturate range, the provided average thoughtput shrinks significantly in stack layer model. This is caused by frequent channel collision, transmission failure and optimized PHY channel error which are computed based on combined layers model as shown in Figure 3. Figure 5b depicts the evolution of time overhead due to CSMA procedure for transmitting each packet successfully. In the heavy network loads of stack model, the expected time overhead increases dramatically. Expanded number of retransmissions attempts cause extra wasted time along with the probability of channel collision $p_{c,f}$ and PHY channel error $p_{e,f}$, respectively. Expected frame retries number $n_{rtx}$ is applied as a coefficient of time expenditure due to frame control message overhead ($T_{IPS}$, $T_{ACK}$, $T_{ACK}^{timeout}$, etc.) for additional delay estimation. Furthermore, time overhead of continual backoff procedure also give rise to additional latency in the range of maximum retransmissions attempts $N_{rtx}$. High data loads have significant impacts on the overall system reliability, as shown in Figure 5c. Stack model obtains more decline trend of reliability performance compared with joint layer model.

For the evaluation of efficient energy consumption, we also rebuild energy consumption estimation module for single MAC layer model [5] and joint model [11] respectively. Additional fixed circuitry energy cost [3] is considered as elementary value $\overline{E}_{c,fixed} = 2.86\mu J/symbol$. As illustrated in Figure 5d, at the range of light offered loads in stack model, effective energy consumption increases linearly with input value $\Phi$. PHY layer model achieves indistinctively outcome of effective energy consumption for reliable transmission compared to the results of signal layer MAC model. The result of joint model in early range can be explicated as its overestimation on systematic performance degradation as the result of the constant PHY channel error estimation. In the situation that $\Phi$ increases to a saturate load level, efficient energy consumption $E^*$ increases dramatically due to the extra wasted energy expenditure under cross-layer constraints model. Evolution indicates that network sacrifice efficiency of overall energy conversion to make up the lack of QoS. Finally, three dimensional surface figure helps us to mimic the multivariate functionalities of stack cross-layer model. Figure 5 presents the sampling observation of effective energy consumption output, which influenced by the input vectors of multivariate parameters (distance $d$, offered loads $\Phi$ and noise level $N_0$). From the evolution of $E^*$ with growing channel noise level $N_0$, region in long distances and saturated data flow show more significant increment. Simulation results are in a good agreement with the interpretations in previous




**(a) Average thoughtput with Information loads**

**(b) Average delay with Information loads**

**(c) Reliability with Information loads**

**(d) Energy consumption with Information loads**

**Figure 4: Performance comparison between Stack cross-layer model and benchmark models**

section. Finally, three dimensional surface figure helps us to mimic the multivariate functionalities of stack cross-layer model. Figure 5 presents the sampling observation of effective energy consumption output, which influenced by the input vectors of multivariate parameters (distance $d$, offered loads $\Phi$ and noise level $N_0$). From the evolution of $E^*$ with growing channel noise level $N_0$, region in long distances and saturated data flow show more significant increment. Simulation results are in a good agreement with the interpretations in previous section.

# 5 CONCLUSION

In this paper, based on the joint layer model [11] with static PHY layer error calculation, we proposed a stack cross-layer model for comprehensive performance analysis of IEEE 802.15.4 network. Adaptive physical channel propagation model is integrated into Markov chain MAC layer model, which is evaluated with multivariate parameter inputs. Network performance are fully assessed under the dynamic interaction from single sublayer models and multi-dimensional parameters environment, respectively. The simulation results in different scenarios verify that multivariate stack model achieves more comprehensive systemic analysis on QoS performance and effective energy consumption, especially allow us to reproduce faithful performance tracking under multi-dimensional parameters. In the future work, multi-hop transmission and different topologies will be considered into the analytical model for different structures of sensor network.

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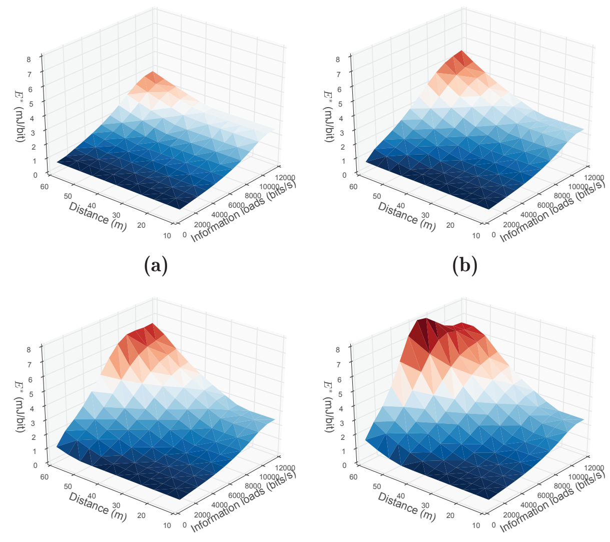


(a) (b) (c) (d)

**Figure 5: 3D plots of effective energy consumption $E^*$ with multivariate parameter sets ($\Phi$, $d$, $N_0$): (a) $N_0$ = 10, (b) $N_0$ = 15, (c) $N_0$ = 18, (d) $N_0$ = 20.**

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