The International Journal of Engineering and Science (IJES)
|| Volume || 6 || Issue || 12 || Pages || PP 36-46 || 2017 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

On Analyzing IoT Networks in Frequency Domain

M.Baz
Computer Engineering Department, College of Computers and Information Technology, Taif University, K.S.A; Corresponding Author: M.Baz

ABSTRACT
The Internet of Things (IoT) networks has becoming pillar in most of the current and foreseen communications systems due to their ability to provide digital skin over physical worlds. This prevalencearisesthe need to investigatebehavior of IoTunder different conditions beforehand real-deployment in order to save money and efforts. Motivated by the fact that most of the current methodologies used to determine performance of ad-hoc and mobile networks are not suitable for IoT due to its strangest characteristic. This paper proposes a novel means to study and compute the performance of IoT without need to involve designers and developers in heavy mathematical nor waste their resources in real test-bed. The proposed tool exploits the metaphors between the probability theory and frequency domain to develop a simple yet accurate technique todetermine IoT metrics. Our approach paves the road towards employing the signal processing techniques such as filters, Fourier transforms and characteristic function of probability distributions in analyzing IoT queuing model under Fading-shadowed channel conditions. Furthermore, this paper provides a circuit layout for determining the throughput and latency of the network. The results of our work have been validated against real testbeds as well as by comparing them with well-known results. This demonstrates high level of accuracy of the proposed tool and their creditability.

Index Terms:*Frequency response, characteristic function, circuit layout, inter-departure distribution.*

Date of Submission: 11-11-2017 Date of acceptance:08-12-2017

I. INTRODUCTION

Success in connected computers and people to the Internet motivated researchers to introduce Internet of Things (IoT) as a means to connect physical objects to the Internet as well [1]. However, one of the key challenges that facing the development and proliferation of IoT is how to find an effective means to analyze and design of these networks beforehand real implementations [1-2]. Although number of simulation platforms have been developed to study mobile and ad-hoc wireless networks and wireless sensor networks. The oddest design philosophy of IoT makes it radically different than other sorts of networks. In other meaning, typical IoT devices are embedded into inhabitant physical objects and communicate globally over the Internet. Owing to the embedding requirement, an IoT device miniaturizes to that scale that makes global communications are overburden. Moreover, considering the natural of most of the channels under which IoT is operating are unreliable adds another dimension of challenge. This in turn, thruststhe need to find alternative platforms to mimic the behavior of IoT under vast operational conditions with high level of accuracy and low cost [1-3].

This paper aims to address the above requirement by analyzing the IoT networks in frequency domain; the key advantages of this approach are multi-faced. Firstly,the ability of frequency analysis to derive a simple interpretationfor complex systemscompared to time domain. Enables us to revel insightful characteristics for the operations ofIoT without embroiling in heavy mathematical. This argument can be justified by considering the large volume of literature that attempted to scrutinizes the effects of unreliable channel conditions on the performance of wireless network. Most of these works encompasses a completed mathematical expression and ends up with no-closed forms. The second support for the need to use the frequency domain in analyzing IoT network is that it facilitates using signal processing techniques to mimic the operations of practical IoT networks. For instance, it will be seen in this paper that the throughput of a network can be obtained by applying a low-pass filter to the aggregated traffic.

The main contribution of this work is to treat the probability distributions characterizing IoT networks operations as signals;thereafter, to employ signal processing techniques to quantify their performance metrics. Based on the outcomes of this contribution, this paper develops the circuit layout of the performance of IoT networks. In order to ensure the seminal of this work, we use both ideal and fading-shadowed channel conditions and using a queuing mode.

The remaining of this paper is organized as following: section II provides overview for the related work, section III discusses the analogies between signal processing and probability distributions and section IV derives characteristic functions of GI/G/1 queue. Section V utilizes results of other sections to compute the characteristic function of successfully received packets over single hop network and section VI defines the circuit layout. Section VII extends the proposed model to cover fading-shadowed channel and results and discussion are given in section VIII. Finally section IX concludes this work.

II. RELATED WORK

The teletraffic theory [4] is a branch of the applied probability that investigates the planning, evaluation, operation and optimization of the communications networks.The teletraffic theory was introduced by Erlang in 1920 to study the statistical characteristics of the telephone networks such as call's probability distributions, their inter-arrival rate, expected service time, etc. The results of that work reveals some of the key aspects of the traffic over telephone networks such as memory less property of the arrival calls and variations of the traffic within time.

Now, after more than a century, the same theory is still used to design and development of the most of modern communication networks. However, these networks are developed in quick pace that increases the complexity and analyzing and push researchers to be more depending on simulator platform. Although, simulator can provide quick and consistent outcomes [5]. Their comparison with real test-bed demonstrates significant differences which can be attributed to the techniques under which simulator engine handle communication channels. Nonetheless, a number of works attempted to revive the analytical models, but a number of challenges were faces. Some of these challenges are presented to account for the reliability of communication media(wireless instead of wired telephone networks), to account for the traffic patterns(long rang dependency instead of memory-less),to account for topology of the network(ad-hoc instead of fixed topology) and to account for the resource management (scarceresources instead of gain resources). These challenges add increase theintractability of classical teletraffic model and necessitates searching for powerful means to enhance the classic teletraffic theory.

This paper proposes a novel approach to analyzethe performance of the communication network with especial emphasis on the Medium Access Control (MAC) protocol, as it is the most important mean that effect the performance of communication networks (being the MAC protocol is response to maintain the collision probability and the energy). The proposal approach analysis the performance of MAC protocols in frequency domain using signal processing techniques and filter design methodology. The advantage of this new approach is enormous; firstly, it simplifies the analysis as it converts the complicated operational on the time domain into a simpler one in frequency domain. Secondly, it facilities analyzing the effects of the wireless propagation model on the performance of the MAC protocol. Thirdly, it enables us to reveal the dynamic characteristics of the MAC protocol and derives the optimal operation conditions of the system.

III. ANALOGY BETWEEN THE SIGNAL PROCESSING AND PROBABILITY DISTRIBUTIONS

This section demonstrates metaphor between the probability distributions and signal processing; which allows usto establish a novel mean to analyze the performance of IoT networks protocols using the signal processing techniques. Ourproposal treats probability distributions of inter-arrival, service and inter-departure traffic as signals whose characteristics can be determined in frequency domains. Table I summarized the key methods by which the analogies between the probability distribution and the signal processing [6].

Table I: Analogies Between Probability Distributions And Signal Processing

Probability	Signal processing
Probability Generating Function (PGF)	z-transform
Moment Generating Function (MGF)	Laplace transform
Characteristic Function (CF)	Fourier transform
Cumulant Generating Function (CGF)	Cepstrum transform

Among these aforementioned expressions, this study emphasis on CFs as they treat the probability distribution is frequency domain. The CF is defined as the Fourier transform of the probability distribution, i.e., for a given random variable X whose probability density is $f_X(x)$, the CF is denoted here by $x(\xi)$and given as:$x(\omega) = E\left(e^{i\xi X}\right) = \int_{-\infty}^{\infty} e^{i\xi x} f_X(x)\, dx$Where E is the expectation operator and $i = \sqrt{-1}$. The CF of maps a random number from the real plane to the perimeter of the unit circle in complex plane where the center of mass of a distribution is wrapped around the unit circle[24-28], i.e.,$|x(\omega)| \leq x(0) = 1$. The CF of a distribution is always existing and unique and k^{th} moment of that distribution can be determined readily using the differential operator.

DOI: 10.9790/1813-0612023646

As this work study the probability distributions that are related to time (inter-arrival, service and inter-departure), the CF expresses this probabilities in unit (rad/seconds).

IV. CHARACTERISTIC FUNCTIONS FOR GI/G/1 QUEUE

This section is devoted to find the inter-departuredistribution of a GI/G/1 queue. It is well known that there is no closed form solution for the inter-departure distributionof this general inter-arrival/general service queue in time domain [7,24-27].

Let $a(\xi)$ be the CF of a general probability distribution that used to generate the inter-arrival timings between packets and let $s(\xi)$ be the characteristic function of a general probability distribution that used to generate of the service time. Finally, let ρ be the utilization factor of a queue which is the ratio between the average service times of packets to the average inter-arrival time of packets, i.e.

$$\rho = \frac{s'(\xi)}{a'(\xi)}|_{\xi=0} \qquad (1)$$

This study assumes that the queue is stable and hence the value of ρ is always less than one. Let us assume thatX_n,S_n and $D_n$are the arrival, service anddeparture times of an arbitrary packet n.The main aim here is to derive the CF of the inter-departure distribution of a GI/G/1 queue [30-33], we distinguish between two cases. Firstly,where packet arrives to find a node is busy in service another packet and secondly when a packet arrives to find a node is idle, Fig.1 shows schematic diagrams of both cases.

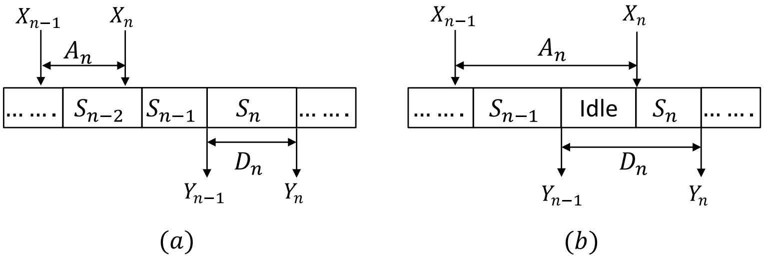

Figure 1. Schematic diagram for the inter-departure process of a queue

The first case occurs when a packet n arrives to find the system busy in servicing other packets, as illustrated in Fig.1-a.In this case the system commences serving packet n only after departing of packet $n-1$, thereby the inter-departure time between packets $n-1$ and n is the time required to service packet n, hence:

$$D_n = S_n \qquad (2)$$

The second case as depicted in figure 1-b occurs when packet n arrives to find the system idle, i.e., packet $n-1$ departs before arriving of packet$n$. In this case the node starts immediately servicing packet$n$. Hence, the inter-departuretime of packets$n-1$ and n is the sum of the inter-arrival time between two packets and the different between service time of them, hence:

$$D_n = A_n + S_{n-1} + S_n \qquad (3)$$

From equations (2) and (3), the CFof the inter-departure time distribution of a GI/G/1 queue, denoted by $d(\xi)$,can be constructed using the theory of mixture probability distribution[5-9].As shown the first case, when a node is busy, which occurs with probabilityρ, the inter-departure distribution is the service time distributionas given in equation (1).When a node is idle which occurs with probability$(1-\rho)$, the inter-departure distribution is the autocorrelation of the service distribution convoluted with the inter-arrival distribution.Thus, the inter-departure distribution is given as:

$$d(\xi) = \rho s(\xi) + (1-\rho)\big(a(\xi)\, s(\xi) s^*(\xi)\big) \qquad (4)$$

where $s^*(\xi)$ is the complex conjugate of the characteristic function of the service time distribution. This result demonstrates one of the benefits of analyzing network in frequency domain, sincereaching such result in time domain requires solving integral Wiener-Hopf equation [16-19] which cannot be done for general queuing model.

DOI: 10.9790/1813-0612023646

V. CHARACTERISTIC FUNCTION OF SUCCESSFUL RECEIVED PACKET OVER SINGLE-HOP NOISE CHANNEL

Let us consider a single hop network consists of N nodes organized in a star topology around the sink. Following the same notations given above, the CF of packet's inter-arrival timings generated by the n^{th} is denoted by$a_i(\xi)$. Furthermore, we assume the all N nodes use a pure ALOHA protocol to access the shared channel. Hence the service time distribution of the $n^{th}$is:

$$s_n(t) = e^{i\xi l} \qquad (5)$$

where l is the length of packets, substituting (5) into (4) yields:

$$d_n(\xi) = \rho_n e^{i\xi l} + (1 - \rho_i)\big(a_n(\xi)\big) \qquad (6)$$

Considering the fact that in ALOHA protocol each node transmits its packet independently of other nodes enables us to derive the inter-arrival distribution of the sink, $a_{sink}(\xi)$, as a multiplication of the inter-departure distribution of N nodes.

$$a_{sink}(\xi) = \prod_{n=1}^{N} d_n(\xi) \qquad (7)$$

More importantly, the probability distribution of the packets that are received successfully by the sink which is denoted by $s_{sink}(\xi)$ can be obtained by eliminating the overlapping interval from $a_{sink}(\xi)$. Hence, $s_{sink}(\xi)$ can be given as:

$$s_{sink}(\xi) = \ (1 - sinc(\xi l))\prod_{n=1}^{N} d_n(\xi) \qquad (8)$$

It is of interest to note that, $s_{sink}(\xi)$ is truncated probability distribution as its integration from 0 to ∞ does not sum to one; instead, this integration represents the aggregated probabilities of the successful packets that are received by the sink. This in turn enables us to compute the throughput, denoted by S, of the network as the average of this probability by the rate of packet generated by all nodes hence:

$$S = \frac{1}{i}\frac{d}{d\xi}\left((1 - sinc(\xi l))\prod_{n=1}^{N} d_n(\xi)\right)|_{\xi=0} \qquad (9)$$

A face validation for equation (9) can be accomplished by comparing the result of this equation versus some throughput equations reported in the literature. For instance, it is well known that the throughput of a network operating slotted ALOHA and consisting of infinite number of nodes each of which is equipped with a buffer adequate for a single packet and generates its traffic according to a Poisson process whose rate is λ_n is given as $S = Ge^{-G}$ where G is the rate of the aggregated traffic offered by all nodes. Considering these assumptions from the perspective of the proposed model yields the following:

1- The assumption that each node has a buffer adequate of a single packet implies that a node cannot generate a new packet while it contends to access the channel, or in other words, the service rate is much large than the arrival rate node which yields $\rho_n \to 0$ [14-15]. Substituting this value into equation (9) yields the probability distribution of inter-departure as $d_n(\xi) = a_n(\xi)$.

2- The assumption that each node generates its traffic according to a Poisson process with rate λ_n implies that the inter-arrival distribution of a node is negative exponential distribution with rate λ_n, hence, $a_n(t) = \lambda_n/(-i\,\xi\, +\, \lambda_n);\, \forall n \in N$

3- The assumption that network operating slotted ALOHA implies that the overlapping interval is 1 as packets is collided only if they are overlapped at the begging of slot.

Substituting these values into equation (9) yields that:

$$S = \frac{1}{i}\frac{d}{d\xi}\Big(\big(1 - sinc(\xi)\big)(1 - i\lambda_n\xi)^N\Big)|_{\xi=0} \qquad (10)$$

Applying little algebra, yields that $S = Ge^{-G}$ which is identical to the well-known equation of slotted ALOHA. Likewise, the throughput of pure ALOHA can be obtained from the proposed model just by replacing the value of the overlapping interval to 2instead of 1 in equation (9) and keeping other parameters to their values. This in turn gives the value of throughput as $S = Ge^{-2G}$ which matching the equation of pure ALOHA reported in the literature.
Since the latency of network is the time differences whenever a packet is commenced for transmission until it has been successfully received be the sink. Form frequency domain perspective, the probability distribution delay can be computed as the phase spectra of the CF of packets received successfully to the sink. Let latency is denoted $\angle s_{sink}(\xi)$.

VI. CIRCUIT LAYOUT FOR THE PROPOSED PLATFORM

The results presented in the previous section exhibitthe solid relationship between the frequency and time domains in the area related to performance evaluation of wireless networks. More importantly, the face validation shows how to obtain the main performance metrics readily in the frequency domain. Here we exploit these results to introduce the circuit layout that can be used to derive the performance metrics. We starts by exhibit the high-level description for the circuit concept thereafter derive the circuit.
Fig.2 illustrates the high-level description of the mathematical model where Fig.2-a shows the inter-arrival, service and inter-departure distributions of three nodes 1,2 and N while Fig.2-b depicts the inter-arrival distribution at the sink, $a_{sink}(t)$. It is of interest to note that the inter-departure distributions of all nodes are truncated over the interval $[0, l]$. This is due to the fact that the inter-departure time between two consequence packets from the same node cannot be less than the time required to service the packet. More importantly, Fig.2-b depicts that the inter-arrival distribution of the sink$a_{sink}(t)$ is continuous over the interval$[0, l]$ which characterises the collision at the sink as two or more packets collide when their inter-arrival times at the sink is less than or equal to the time requires to receive the packet, i.e., l. Therefore, multiplying $a_{sink}(t)$ by a unit step function shifted by l (i.e., $u(t - l)$) which is shown in Fig.2-c yields the inter-arrival distribution of successful packets that are received the sinkwhich was denoted by $s_{sink}(t)$ and shown in Fig.2-d.

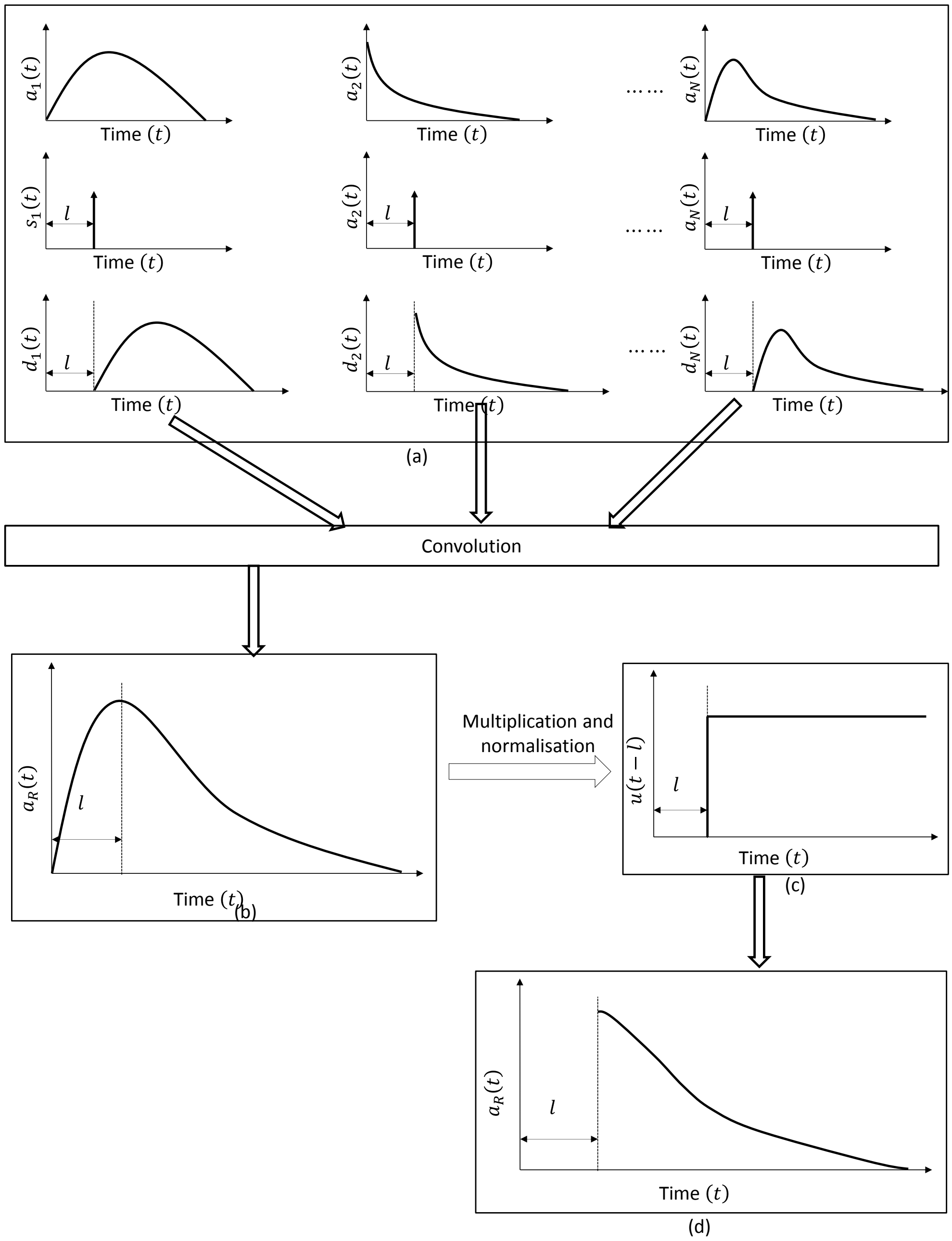

Fig.2 high-level description for the mathematical model

Considering the appealing features of the frequency domain and transformation between it and time domain, yields the following circuit layout for analyzing of IoT network in frequency domain.

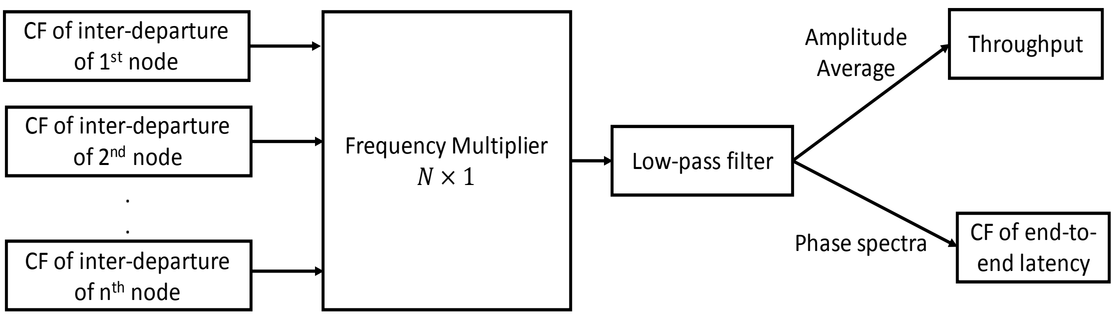

Fig. 3 Circuit layout for frequency response of IoT networks

The main input for the circuit diagram are the CFs of the inter-departure of packets generated by N nodes, these functions can be obtained by applying (4) for an assumed inter-arrival CFs. The second phase of the proposed circuit is to multiply all the inter-departure CFs; this is equivalent to the convolution of inter-departure distribution illustrated in Fig.2. This multiplying in frequency domain or convolution in time domain represents the inter-arrival distribution of the aggregated packets are sent towards the sink, which is given in equation (7). The third phase of the proposed circuit which is the low pass filter is used to eliminate overlapping between received packets. It is of interest to note that the cutoff frequency of this filter is the rate with which the sink cannot encode the received packet correctly. Hence under ideal channel condition is the time required to send the packet which is denoted by l in equation (8) onwards. Indeed, the low pass filter in frequency domain serve the same purpose that rectangular function does in time domain as shown in Fig.2-c. Hence the output of this phase is the CF represents the successfully packets as seen by the sink.Thereafter, the final phase of the circuit can be used to obtain the throughput and latency of network. Since the Fourier transform is a complex function it can be characterized by amplitude and phase spectra.Taking into account that the amplitude function represents the intensity of the CF with respect to the frequency facilitates computing the throughput of network as the average of this function. Moreover, bearing in mind that the phase spectra of the CF of packet received successfully by the sink is nothing more than the latency of packets, enabling us to derive the latency as the average of phase spectra.

VII. EXTENSION OF THE PROPOSED TOOL OVER FADING-SHADOWED CHANNEL

This section extends the results derived in previously to compute the throughput-delay characteristic over noisy channel. Let C_{xy} be a random variable representing the channel losses over the link that connects an IoT node $n; n \in N$ and the sink. Under a shadowed fading channel, the value of C_n is:

$$\begin{aligned} C_n &= PL_0 + 10\alpha_n \log_{10}\left(\frac{d_n}{d_0}\right) + E_n + F_n \\ &= K_n + E_n + F_n \end{aligned} \quad \text{dB} \qquad (11)$$

Where:

1) PL_0 is the path-loss over the reference distance$d_0$and α_n is the path-loss exponent over distance between the n^{th}node and the sink, i.e.,d_n. Since we consider stationary IoT network, the first two terms are constant denoted here by K_n and its CF is $K_n(\xi) = e^{i\xi K_n}$.

2) $E_n$is a random variable representing the large-scale shadowing which is distributed normally with zero mean and σ_n standard deviation. The CF of S can be given as$E_n(\xi) = e^{-0.5(\xi\sigma_n)^2}$.

3) F_n is a random variable representing the logarithmic fading following log-Weibull distribution [24-25] whose shape and scale parameters denoted by $\gamma_n$and$\nu_n$respectively. The log-Weibull has been selected in this study as it has a closed form expression and can be used to model other small-scale shadowing models [26]. The CF of F_n is$F_n(\xi) = \Gamma(1 - i\nu_n\xi)e^{i\xi\gamma_n}$, where $\Gamma(\cdot)$ is the Gamma function.

Based on the aforementioned assumptions the characteristic function of channel losses between the n^{th} node and the sink is:

$$c_n(\xi) = \Gamma(1 - i\,\nu_n\xi)e^{i\xi\left(0.5i\xi\sigma_n{}^2 + \gamma_n + K_n\right)} \qquad (12)$$

Considering that the CFs of channel losses and inter-departure are pairwise mutual independent facilities presenting of joint CF of them as:

$$g_n(\xi_1, \xi_2) = d_n(\xi_1)c_n(\xi_2) \qquad (13)$$

Considering the fact that the channel conditions are independent of traffic and that in ALOHA all nodes transmit their packet without respect to other, yields that the joint CFs of the inter-arrival of packets and their received power, denoted by $g_n(\xi_1, \xi_2)$, is multiplication of both CFs as shown in equation (13). Moreover, the aggregated signal received the sink is the product of all joint CF, i.e., $a_{sink}(\xi_1, \xi_2) = \prod_{n=1}^{N} g_n(\xi_1, \xi_2)$. The next step towards find the throughput and average latency is to compute the CF of those packets that are received successfully by the sink, i.e.,$s_{sink}(\xi_1, \xi_2)$. Over noisy channel, a packet is received successfully if its power with respect to all noisesand interferences is higher than the capture ration of the sink, denoted here by θ.From frequency domain perspective, the $s_{sink}(\xi_1, \xi_2)$ can be obtained by applying afilter that can detect the signal that has the highest amplitude amongst the overlapped signals and compares it with respect to c. From a frequency response perspective, this is a gaussian filter whose mean isthe receiver sensitivity of the sink, denoted by $\psi$and whose variance is capture ratio θ, i.e.,

$$\mathcal{s}_{sink}(\xi_1, \xi_2) = \left(e^{i\psi\xi_1 - \frac{1}{2}\theta^2 {\xi_3}^2}\right)\prod_{n=1}^{N} g_n(\xi_1, \xi_2) \qquad (14)$$

Now the throughput and delay can be computed as the average of amplitude and phase spectra of equation(8).

VIII. RESULTS AND DISCUSSION

This section is devoted to validating the integrity of the proposed tool by comparing its outcomes with those pairs of real test bed. Hence 500 IoT nodes have been deployed over a $50 \times 50 \times 50\ m^3$ area where each node is embedded into an applicant to mimic the real operations of IoT networks. Each node is equipped with a transceiver, battery as well as a set of sensors like temperature, humidity and light. Each node samples the physical quantity and send the readings to the sink that is located with the line of sight in respect to all nodes. Sampling of test bed physical channel were gathered and fitted into the parameters of the fading-shadowed model developed in this paper [8-13]. The data rate of the network is set at 250Kbps operating under 2.5GHz frequency unlicensed band. In terms of protocol stack, each node uses the ALOHA protocol to access the shard channel and addresses according to IPv6 protocol. owing to the overhead of IPv6 on the lifetime of the nodes, the deployment testbed uses the 6LoWPAN protocol with network discovery protocol and orthogonal addressing scheme. Packets are generated according to Poisson processwhose rate is adjusted according to the offered load. In order to ensure 95% confident intervals of the collected readings, the experiment repeated 100 times each of which continued until all devices are die out. These readings then compared to the results of the proposed mathematical model which then used to revel the difference between them and illustrate them in Fig. All of these figures demonstrate the ability of our tool to match the outcomes obtained from testbeds with high level of accuracy. This highlights the capability of frequency domain in analyzing IoT networks.

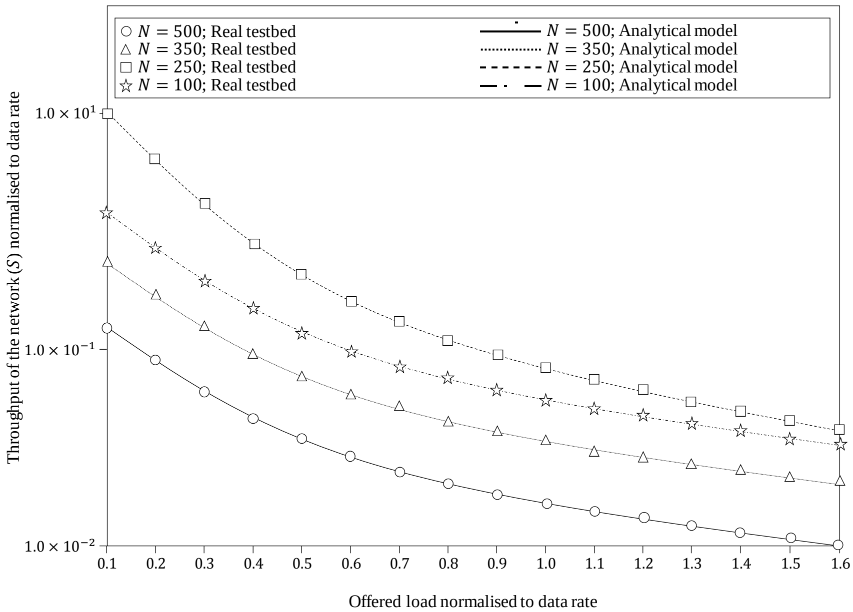

Fig.4 Offered load vs throughout under ideal channel conditions

This figure shows that under ideal channel conditions, the throughput of the network is reduced whenever the offered load is increased. The reason behind that is the characteristic of ALOHA protocol that allows a node to send their packets without prior coordination with other peers. This figure also shows that the throughput of the network is inversely proportional to the number of nodes contending for the channel increase. This is due to the fact that the possibility of collision increases with the number of nodes; however, it such relation is not linear. It can be seen for instance that the maximum achieved throughput of a network consisting of 500 nodes is about one-tenth ofthroughput of 100 nodes network. Such behavior shows the effects of number of nodes is more significant than effect of the offered traffic.

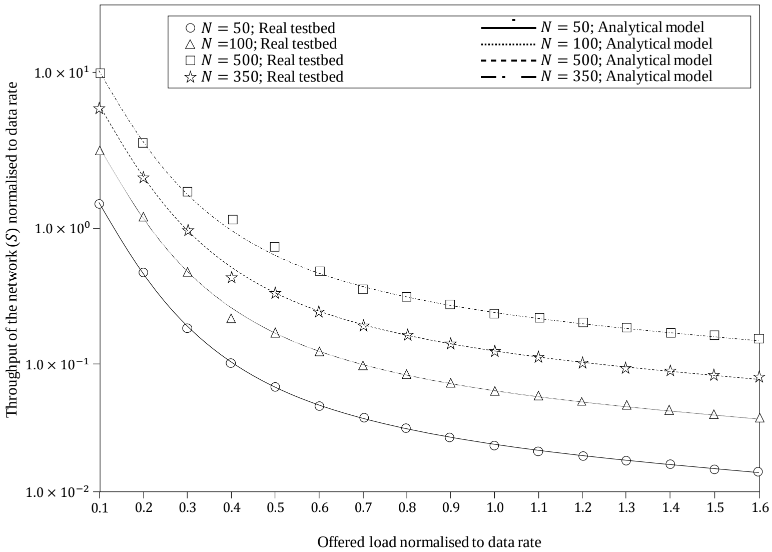

Fig.5 Offered traffic vs throughout under noisy channel

Fig. shows that replacing the ideal channel with fading-shadowed and keeping other parameters to the same values results in much reduction in the value of throughput [20-23]. This result isnatural, as transmission over noise channel increases the possibility of bit error rate which in turn reduces the throughput. Form perspective of frequency domain analysis, equation (8) shows that the throughput is controlled by the area of Gaussian filter which is limited to one.

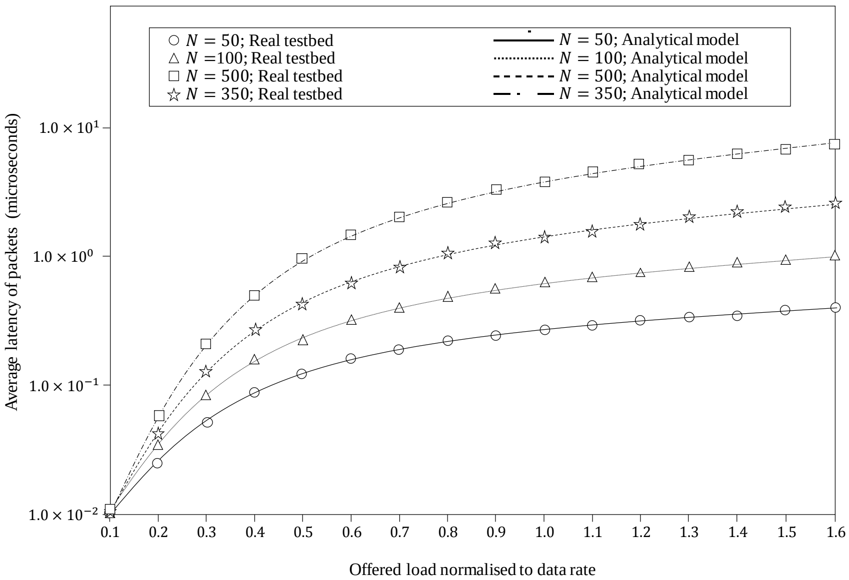

Fig.6 Offered traffic vs average latency under ideal channel

Results of average latency vs offered load under ideal channel show that the increasing number of nodes leads to increase the latency proportionally. For instance, under the same offered traffic the average latency can be increased by about 100 folds when the number of nodes increases by 10 time. The effects of increased offered traffic on the average latency is also proportional as shown in the above figure. Comparing the characteristics of average latency and throughput demonstrates that reduction increasing the offered traffic or number of nodes yields an increasing in average latency and reduction in throughput.

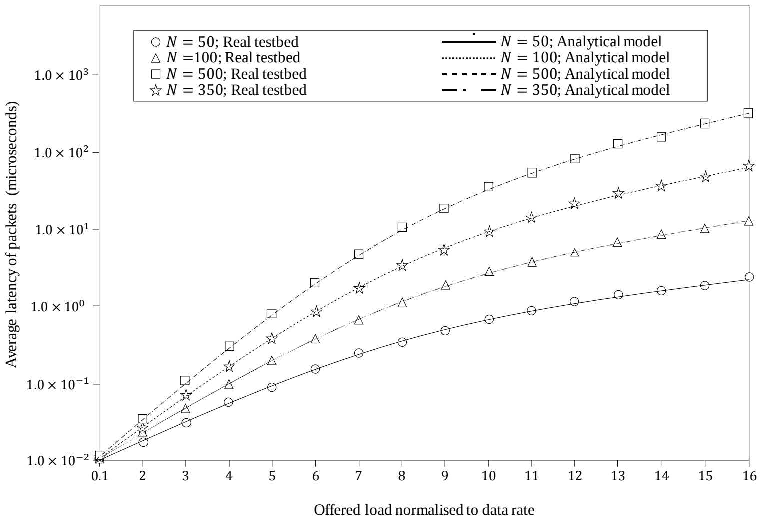

Fig.7 Offered traffic vs average latency under noisy channel

Figure 7 shows average latency vs offered traffic under fading-shadowed channel conditions, it can be seen from this figure how growing of traffic can upsurge the average latency when the noisy channel is employed. The rate with which this increasing is happing is much more than in ideal channel which highlighted the influences of noise on IoT networks.

IX. CONCLUSION

Motivated by the important and prevalence of the Internet of Things networks, and the need to find an accurate, yet a versatile tool to assess its performance under different operational conditions. Without involving the designers and developers to be involved in heavy mathematical nor employment moderate outcomes of simulators. This paper has been introduced a novel tool to determine the throughput and average latency using frequency domain representation of IoT networks. The proposed work considered different channel conditions and employed queuing models which yields a high level of accuracy compared to the real testbed. The results of this work constitute a solid milestone in employing signal processing techniques in teletraffic engineering which can be exploited to extend the capability of current approaches to meet the rapid development of communication systems.

REFERENCES

[1] Samuel Greengard, *The Internet of Things,The MIT Press Essential Knowledge series,* MIT Press, 2015.

[2] Qusay F. Hassan, Atta ur Rehman Khan, Sajjad A. Madani, *Internet of Things: Challenges, Advances, and Applications,* CRC Press, 2017.

[3] Hongjian Sun, Chao Wang, Bashar I. Ahmad, *From Internet of Things to Smart Cities: Enabling Technologies,* CRC Press, 2017.

[4] E. Brockmeyer, H. L. Halstrøm, and A. Jensen, B, *The life and works of A. K. Erlang*, Trans. Danish Acad. Tech. Sci., no. 2, p. 277, 1948.

[5] G. D'Angelo, S. Ferretti, V. Ghini, "Simulation of the internet of things", *2016 International Conference on High Performance Computing Simulation (HPCS)*, pp. 1-8, July 2016.

[6] Robert M. Gray, Lee D. Davisson, *An Introduction to Statistical Signal Processing*, Cambridge University Press, 2004.

[7] Soeren Asmussen, *Applied Probability and QueuesVolume 51 of Stochastic Modelling and Applied Probability,* Springer Science & Business Media, 2008.

[8] Gungor, V.C.; Bin Lu; Hancke, G.P.; , "Opportunities and Challenges of Wireless Sensor Networks in Smart Grid," *Industrial Electronics, IEEE Transactions on* , vol.57, no.10, pp.3557-3564, Oct. 2010.

[9] J. Mišic and V. Mišic, "Access delay for nodes with finite buffers in IEEE 802.15.4 beacon enabled PAN with uplink transmissions," *Computer Communications*, vol. 28, no. 10, pp.1152–1166, Jun. 2005.

[10] X. Li, et al. "Four-dimensional Markov Chain Model of Single-hop Data Aggregation with IEEE 8 .15.4 in Wireless Sensor Networks," *Wireless Network*, vol.18, no.5, pp. 469-479, 2012.

[11] A. Faridi, et al. "Comprehensive Evaluation of the IEEE 802.15.4 MAC Layer Performance With Retransmissions," *IEEE Transactions on Vehicular Technology*,vol.59, no.8, pp.3917-3932, 2010.

[12] Y. Huang, et al. "A Comprehensive Analysis of Low-Power Operation for Beacon-enabled IEEE 802.15.4 Wireless Networks," *IEEE Transactions on Wireless Communications*, vol.8, no. 11, pp.5601-5611, 2009.

[13] C. Jung, et.al, "Enhanced Markov Chain Model and Throughput Analysis of the Slotted CSMA/CA for IEEE 802.15.4 Under Unsaturated Traffic Conditions," *IEEE Transactions on Vehicular Technology*, vol.58, no.1, pp.473-478, 2009.

[14] R. Boucherie and N. Dijk, *Queueing Networks: A Fundamental Approach*, Springer Science & Business Media, 2010.

[15] M. Reiman, "Asymptotically exact decomposition approximations for open queueing networks," *Operations Research Letters*, vol.9, no.6, pp.363-370, 1990.

[16] A. Seidmann, P. Schweitzer, and S. Shalev-Oren, “Computerized Closed Queueing Network Models of Flexible Manufacturing Systems,” *Large Scale Systems*, vol. 12, pp. 91-107, 1987.

[17] P. Denning and J. Buzen, "The operational analysis of queueing network models", *ACMComputer Surveys*, vol. 10, no. 3, pp.225 - 261, 1978.

[18] D. Yao and J. Buzacott, “The exponentialization approach to flexible manufacturing system models with general processing times,” *European Journal of Operational Research*, vol.24, no.3, pp.410-416, 1986.

[19] G. Bitran, and R. Morabito, “Open Queuing Networks: Optimisation and Performance Evaluation Models for Discrete Manufacturing Systems,” *Production and Operations Management*, vol.5, no.2, pp.163-193, 1996.

[20] M. Goyal, et al. “A Stochastic Model for Beaconless IEEE 8 .15.4 MAC Operation,” *Computer Communications*, vol. 34, no.12, pp.1460- 1474, 2011.

[21] Y. Huang, et al. “A Comprehensive Analysis of Low-Power Operation for Beacon-enabled IEEE 802.15.4 Wireless Networks,” *IEEE Transactions on Wireless Communications*, vol.8, no. 11, pp.5601-5611, 2009.

[22] P. Park, et al., “A Generalized Markov Chain Model for Effective Analysis of Slotted IEEE 802.15.4,” *in Proc. The 6th IEEE International Conference on Mobile Ad hoc and Sensor Systems*(MASS), pp.130-139, 2009.

[23] T. Czachórsi, et al., “A Diffusion Approximation Model for Wireless Networks Based on IEEE 802.11 Standard,” *Computer Communications*, vol. 33, Supplement.1, pp.S86-S92, 2010.

[24] G. Levitin, *The Universal Generating Function in Reliability Analysis and Optimization*, Springer Science & Business Media, 2006.

[25] H. Kobayashi, B. Mark and W. Turin, *Probability, Random Processes, and Statistical Analysis: Applications to Communications Signal Processing, Queueing Theory and Mathematical Finance*,Cambridge University Press, 2011.

[26] N. Ushakov, *Selected Topics in Characteristic Functions*, VSP, 1999.

[27] Ch. Charalambides, *Combinatorial Methods in Discrete Distributions*, Wiley-Interscience, 2004.

[28] R. Schinazi, *Classical and Spatial Stochastic Processes*, Birkhäuser, 1999.

[29] L. Kleinrock, *Communication Nets: Stochastic Message Flow and Delay*. McGraw- Hill, 1964.

[30] P. Burke, “The Output of a Queuing System”, *Operation Research*, vol.4, no.6, pp.699–704, 1956.

[31] W. Whitt “Approximations for Departure Processes and Queues in Series,” *Naval Research Logistics Quarterly*, vol. 31, pp.499 - 521, 1984.

[32] E. Gelenve, and I.Mitrani, *Analysis and Synthesis of Computer Systems*, Academic, new York, 1980.

[33] T. Czachórsi, et al.,*Network Performance Engineering, A Handbook on Convergent MultiService Networks and Next Generation Internet*, Springer, 2011.

M.Baz"On Analyzing IoT Networks in Frequency Domain.” The International Journal of Engineering and Science (IJES), vol. 6, no. 12, 2017, pp. 36-46.