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Jitter analysis of real-time services in IEEE 802.15.4 WSNs and wired IP concatenated networks

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Abstract

It is challenging and significant to explore the impacts of non-real-time services on real-time services from the perspective of jitter. Most of current researches on jitter made too many mathematical hypotheses on networks and traffic. This paper puts forward a tandem queuing model to characterize the real communication scenario where heterogeneous services are served by IEEE 802.15.4 wireless sensor networks (WSNs), and then the packets served successfully are fed to Internet protocol (IP) networks. By analyzing the contention access processes in IEEE 802.15.4 WSNs, the authors derive the departure processes of the two types of services, i.e., the arrival processes of IP networks. The IP network is modeled as a queuing system, in which the real-time service is forwarded accompanied by the non-real-time service. Investigating the jitter of real-time services is intractable. Therefore, this paper abstracts this problem as a dynamic queuing system evolving on a dynamic time interval. Referring the transient analysis method (TAM), this paper obtains the queue length in a random time interval which is scaled by the arrival of real-time services. Queue length evolution is closely connected with the jitter. Benefiting from the derivation in probability generation domain, the jitter of real-time services is obtained.

Keywords jitter, heterogeneous M2M services, transient analysis, IEEE 802.15.4 WSNs, IP networks

1 Introduction

The machine to machine (M2M) communication has been identified as one of key drivers to guide the design of the fifth generation (5G) networks. The 5G M2M network is expected to satisfy different quality of service (QoS) requirements for various types of services. According to the difference in delay tolerance, M2M services may be roughly divided into two classes: real-time services (low-rate video monitoring services) and non-real-time services (many kinds of small data services). Real-time services usually require strict QoS constraints not only on delay but also, even much stricter, on jitter. However, the researches on jitter are seldom to be reported due to its complexity in mathematics. We elaborate our research based on the typical M2M communication scenario where two types of services access to IEEE 802.15.4 WSNs, and then are served by IP core networks, as shown in Fig. 1. We are interested in the impacts of non-real-time services on real-time services. We focus on the analysis of jitter which is caused by the non-real-time service and experienced by the real-time service.

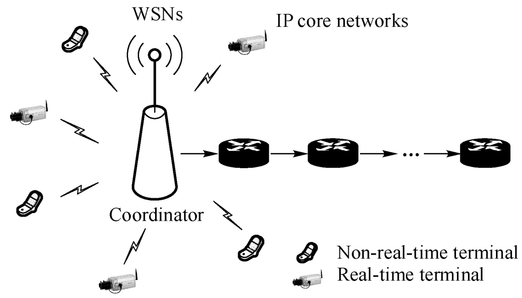

Fig. 1 IEEE 802.15.4 WSNs and IP concatenated networks communication scenario

Most of the researches on IEEE 802.15.4 medium access control (MAC) focused on optimizing carrier sense multiple access with collision avoidance (CSMA/CA) algorithms and QoS performances [1–5]. They modeled

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MAC of IEEE 802.15.4 and evaluated the system throughput and delay. However, the difference of delay, defined as jitter [6], is an important QoS parameter especially for real-time services. Jitter evaluation is a significant and complicated work. In Ref. [7], Huo analyzed the jitter of real-time services in wireless networks. He assumed that each sub-system of the transmission network was a black box and ignored the fundamental communication technologies, such as protocols.

There exist some works on analyzing the jitter in IP networks. All of these works have great value in theoretical aspect. However, they made too many mathematical hypotheses on networks and traffic. The jitter incurred by a periodic traffic was estimated in Ref. [8]. Considering the arrival processes of packets are far from periodic in IP networks, Dohmouni et al. [9] computed the jitter for Poisson arrival. Further, Geleji et al. [10–11] evaluated the jitter for Markov-modulated Poisson process (MMPP) arrival and interrupted Poisson process (IPP) arrival, respectively. Poisson models might not be accurate in general, therefore, Dbira et al. evaluated the jitter for non-Poisson first come first serve (FCFS) queue with a single flow [12]. Most of the researches on jitter were based on steady-state analysis methods (SAM) [13]. However, some significant characteristics of jitter, such as the probability distribution cannot be obtained by steady-state analysis. Therefore, Osterbo et al. [14–15] deployed their researches based on TAM and obtained the delay and jitter, which provided a reference for our work. In aforementioned works, the traffic arriving at IP networks is approximated as a distribution. There exists a gap between the assumption and the reality due to the fact that the input traffic of wired IP networks is decided by the output traffic of wireless networks.

At the same time, above-mentioned works only considered the single node systems (i.e., wireless networks or wired networks). The real network is usually multi-node systems. Focusing on concatenated networks analysis, Chi et al. [16] mainly investigated the IEEE 802.11 wireless local area networks (WLANs) and the IP tandem queuing network. They investigated the delay, throughput and packet loss rate. Nevertheless, the jitter was not considered and only one type of service was involved in their targeted networks.

In this paper, we devote ourselves to analyzing the jitter of real-time services in IEEE 802.15.4 WSNs and wired IP concatenated networks. We formulate our problem as the analysis of the queue evolution over random time intervals. The time interval is decided by the arrival process of real-time services in the IP network. We observe the queue length at every time moment when the packet of the real-time service arrives. We deduce the evolution of the queue length which is closely associated with the jitter of real-time services. The length of time interval which generated by real-time services is random, and also the number of arrival packets of non-real-time services is stochastic. These two folds of random features challenge jitter analysis. We rise to the challenges from these difficulties. Our main contributions can be summarized as follows.

First, we introduce a tandem queuing model to describe the communication scenario that the heterogeneous services contend for the channel access in IEEE 802.15.4 WSNs, and then they depart from the access node and are delivered to IP core networks.

Subsequently, under the heterogeneous M2M services arrivals, we model CSMA/CA process based on Markov theory and obtain the packets departure processes of real-time services and non-real-time services which intrinsically are the arrival processes of IP core networks.

Finally, with the help of transient analysis methods, we derive the queue length in a random time interval which is scaled by real-time services arrival. The variation in queue length is tightly related to the jitter. Benefiting from the processing in probability generation domain, we obtain the jitter distribution of real-time services. Further, we evaluate the jitter of real-time services under different parameters setting of the access procedure in IEEE 802.15.4.

To the best of our knowledge, this is the first work that thoroughly investigates the jitter of real-time services which suffers from the arrival of non-real-time services in wireless and wired concatenated networks.

This paper is organized as follows. Sect. 2 formulates the queuing model from IEEE 802.15.4 WSNs to IP core networks. In Sect. 3, we deduce the departure processes of the heterogeneous services. Sect. 4 presents the solving processes of jitter based on transient analysis methods. Simulations and conclusions are demonstrated in Sect. 5 and Sect. 6, respectively.

2 Queuing model of WSNs and IP concatenated networks

A typical wireless (IEEE 802.15.4) and wired concatenated network is shown in Fig. 1.

The tandem queuing model corresponding to Fig. 1 is depicted in Fig. 2. As shown in Fig. 2, two-state Markov-modulated Bernoulli process (MMBP-2) and interrupted Bernoulli process (IBP) are used to model the arrival processes of real-time services and non-real-time services, respectively [13]. The average arrival rates of real-time services and non-real-time services are λ_{R} and λ_{NR}, respectively. There are M_{R} real-time terminals and M_{NR} non-real-time terminals. The CSMA/CA contention access processes in IEEE 802.15.4 for two types of services are modeled as random distributions G_{R} and G_{NR} respectively. The real-time service and the non-real-time service are transmitted to the IP core network and served there. We assume that service process of IP core networks follows deterministic distribution, which is reasonable for wired networks.

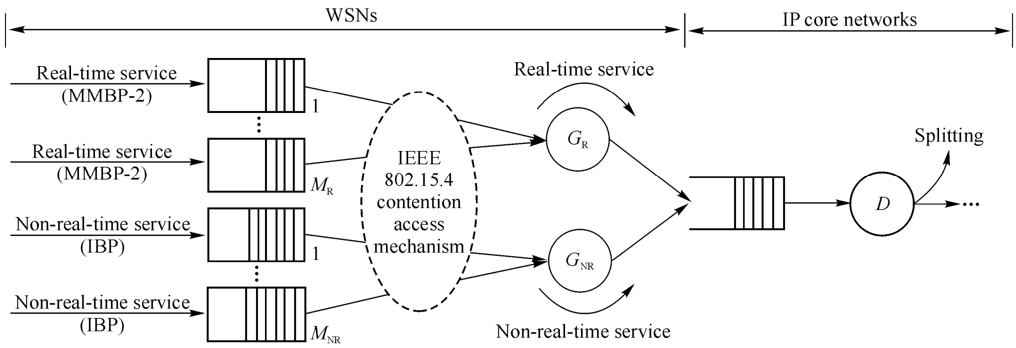

Fig. 2 IEEE 802.15.4 WSNs and IP tandem queuing networks model

3 Analytical model of IEEE 802.15.4 MAC

In this section, we model CSMA/CA process and get the service distributions of the two types of services (real-time services and non-real-time services) in IEEE 802.15.4 WSNs based on the Markov theory.

In Ref. [4], Zhu et al. modeled CSMA/CA in homogeneous terminals scenario. In order to decrease the complexity and apply the consequence presented in Ref. [4], we map the arrival characteristics of two types of terminals into one type of terminal according to the differences of arrival rates. Therefore, when deriving the service process of the non-real-time service, the WSN is taken as a system with $M_{\mathrm{E,\,NR}}$ homogeneous equivalent terminals. The equivalent number of non-real-time terminals is

$$M_{\mathrm{E,\,NR}} = M_{\mathrm{NR}} + \left(\frac{\lambda_{\mathrm{R}}}{\lambda_{\mathrm{NR}}}\right) M_{\mathrm{R}} \tag{1}$$

Referring to Ref. [4], we can obtain the probability generating function (PGF) of the service time of non-real-time services $G_{\mathrm{NR}}(z)$. In the same way, the PGF of the service time of real-time services $G_{\mathrm{R}}(z)$ can be derived. In Ref. [17], Zhai et al. proved that the general distribution can be approximated as exponential distribution. In addition, the service time of non-real-time services can be regarded as an exponential distribution indicates that the number of served successfully packets is a Poisson process. So, the PGF $G_{\mathrm{NR}}(z)$ is fitted as

$$L_{\mathrm{NR}}(z) = \mathrm{e}^{\eta_{\mathrm{NR}}(z-1)} \tag{2}$$

where η_{NR} is the Poisson distribution parameter and it can be obtained by Ref. [2].

4 Jitter analysis of real-time services

The departure processes L_{NR} and G_{R} are two stochastic arrival processes of IP core networks. We observe the evolution of queue length at every moment when packets of real-time services arrive. Let q_{θ}^{N}, $N = 1, 2, \ldots, k_{\theta}$ denote the length of queue where packets are waiting to be served at slot $t_{\theta} + N$. The variation of queue length is closely connected with the jitter of real-time services. The difficulty lies that both the arrival moment of real-time services packets and the number of arriving non-real-time services packets are random.

In order to defeat the difficulty caused by the folded stochastic feature, we analyze the evolution of queue length at every moment, and we establish the relationship of queue length between the arrivals of successive real-time services packets by taking advantage of the recurrence relation in queue length. Further, according to the definition of jitter and the relation between the delay and queue length, we can get the probability distribution of the jitter.

4.1 Queuing model

Jitter is the difference of the delay for two successive packets of real-time services according to the definition of the jitter in Internet engineering task force (IETF) [6].

Fig. 3 eminently shows the evolution of queue length between θth and $(\theta+1)$th arriving packets of real-time services. There are random amount of packets of non-real-time services arriving in the time interval k_θ which is scaled by the successive real-time services packets. The delay of current real-time services packet equals to the queue length of current moment due to the fact that each packet requires a single time slot to be served. We can derive the jitter of real-time services as long as we get the difference of queue length. In this subsection, we analyze the queue length in every slot.

We focus on the queue length evolution of θth arriving packet and $(\theta+1)$th arriving packet of real-time services. We define the length of packet is one slot. According to Fig. 3, we can obtain the dynamic functions of the queue length as follow without considering the queue is empty.

$$q_\theta^1 = q_\theta + l_\theta^1 + 1 - 1 = q_\theta + l_\theta^1 \tag{3}$$

$$q_\theta^N = q_\theta^{N-1} + l_\theta^N - 1;\quad N = 2, 3, 4 \cdots k_\theta \tag{4}$$

$$q_\theta^{k_\theta} = q_{\theta+1} \tag{5}$$

where q_θ is the queue length at the end of the slot t_θ. $l_\theta^N\left(N = 1, 2, \ldots, k_\theta\right)$ denotes the arrived amount of non-real-time services packets.

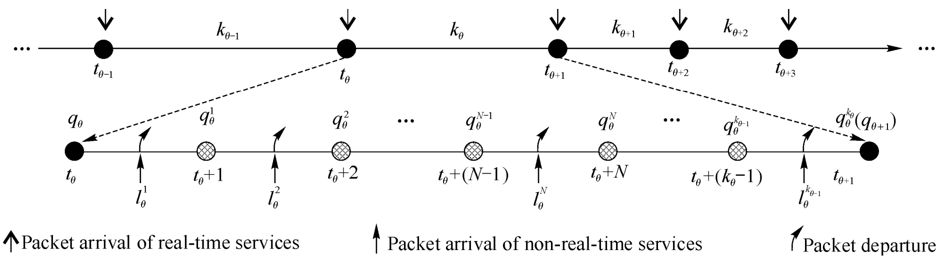

Fig. 3 Transient change of queue length

4.2 Evaluating the jitter

In order to analyze the relationship in the queue lengths at every slot in the probability domain. We transform Eqs. (3)–(5) to corresponding probability generating functions and solve the equations in the generation function domain. We introduce the joint generating function which takes the evolution of the queue length and the arrival moment of real-time services into account. We define $F_\theta\left(z,x\right) = E[z^{q_\theta} x^{t_\theta}]$ as the joint generating function of q_θ and t_θ, and we define the joint generating function of q_θ^N and t_θ under the condition of $t_{\theta+1} - t_\theta = k_\theta$ as $F_\theta^N\left(z,x\right) = E\,[z^{q_\theta^N} x^{t_\theta} \mid k_\theta]$, $N = 1, 2, \ldots, k_\theta$. By applying the queuing relations, we find the following recursions.

$$F_\theta^1\left(z,x\right) = E[z^{q_\theta^1} x^{t_\theta} \mid k_\theta] = E[z^{q_\theta + l_\theta^1} x^{t_\theta} \mid k_\theta] = F_\theta\left(z,x\right) L_{\mathrm{NR}}\left(z\right) \tag{6}$$

$$F_\theta^N\left(z,x\right) = E[z^{q_\theta^N} x^{t_\theta} \mid k_\theta] = E[z^{q_\theta^{N-1} + l_\theta^N - 1} x^{t_\theta} \mid k_\theta] = F_\theta^{N-1}\left(z,x\right) L_{\mathrm{NR}}\left(z\right) z^{-1};\quad 2 \leqslant N \leqslant k_\theta \tag{7}$$

Eq. (7) establishes the relation of queue length between the slot $t_\theta + N$ and the slot $t_\theta + N - 1$. We can get $F_\theta^{k_\theta}\left(z,x\right)$ as a function of $F_\theta\left(z,x\right)$ by solving Eq. (7) recursively.

$$F_\theta^{k_\theta}\left(z,x\right) = F_\theta^{k_\theta - 1}\left(z,x\right) L_{\mathrm{NR}}(z) z^{-1} = \ldots = F_\theta^1(z,x)(L_{\mathrm{NR}}(z) z^{-1})^{k_\theta - 1} = F_\theta(z,x) L_{\mathrm{NR}}(z)(L_{\mathrm{NR}}(z) z^{-1})^{k_\theta - 1} \tag{8}$$

The inter-arrival time of real-time services packets and the number of arrived non-real-time services packets are stochastic, which depend on the service of IEEE 802.15.4. In Sect. 3, we have deduced the PGF of the inter-arrival time of real-time services $G_{\mathrm{R}}(z)$. By taking inverse transform of $G_{\mathrm{R}}(z)$ [18], we can obtain its probability mass function $g_{\mathrm{R}}(y)$. Taking every inter-arrival time of real-time services packets into consideration, we can derive the joint generating function of queue length and time in slot $t_{\theta+1}$.

$$F_{\theta+1}(z,x) = \sum_{k_\theta = 1}^{\infty} g_{\mathrm{R}}(k_\theta) E[z^{q_{\theta+1}} x^{t_{\theta+1}} \mid k_\theta] = \sum_{k_\theta = 1}^{\infty} g_{\mathrm{R}}(k_\theta) x^{k_\theta} E\,[z^{q_\theta^{k_\theta}} x^{t_\theta} \mid k_\theta] =$$

$$\sum_{k_\theta=1}^{\infty} g_{\rm R}(k_\theta) x^{k_\theta} F_\theta^{k_\theta}(z,x) =$$
$$\sum_{k_\theta=1}^{\infty} g_{\rm R}(k_\theta) x^{k_\theta} z F_\theta(z,x)(L_{\rm NR}(z)z^{-1})^{k_\theta} =$$
$$zF_\theta(z,x)\sum_{k_\theta=1}^{\infty} g_{\rm R}(k_\theta)(xL_{\rm NR}(z)z^{-1})^{k_\theta} =$$
$$zF_\theta(z,x)G_{\rm R}(xL_{\rm NR}(z)z^{-1}) \tag{9}$$

Eq. (9) establishes the relation between $F_{\theta+1}(z,x)$ and $F_\theta(z,x)$. Let $t_0 = 0, q_0^1 = \varepsilon$, recursively, we have

$$F_\theta(z,x) = z^\theta F_0(z,x)(G_{\rm R}(xL_{\rm NR}(z)z^{-1}))^\theta =$$
$$z^\theta E[z^{q_0} x^{t_0}](G_{\rm R}(xL_{\rm NR}(z)z^{-1}))^\theta =$$
$$z^\theta E[z^{q_0^1 - l_0^1} x^{t_0}](G_{\rm R}(xL_{\rm NR}(z)z^{-1}))^\theta =$$
$$z^\varepsilon L_{\rm NR}^{-1}(z)(zG_{\rm R}(xL_{\rm NR}(z)z^{-1}))^\theta \tag{10}$$

In order to derive the joint probability generating function at every arrival moment of real-time services packets, we introduce the generating function $F(z,x,s) = \sum_{\theta=1}^{\infty} s^{\theta-1} F_\theta(z,x)$. Therefore, we have

$$F(z,x,s) = \sum_{\theta=1}^{\infty} s^{\theta-1} F_\theta(z,x) =$$
$$\sum_{\theta=1}^{\infty} s^{\theta-1} z^\varepsilon L_{\rm NR}^{-1}(z)(zG_{\rm R}(xL_{\rm NR}(z)z^{-1}))^\theta =$$
$$z^{\varepsilon+1} L_{\rm NR}^{-1}(z) G_{\rm R}(xL_{\rm NR}(z)z^{-1}) \cdot$$
$$\sum_{\theta=1}^{\infty} [szG_{\rm R}(xL_{\rm NR}(z)z^{-1})]^{\theta-1} =$$
$$\frac{z^{\varepsilon+1} L_{\rm NR}^{-1}(z) G_{\rm R}(xL_{\rm NR}(z)z^{-1})}{1 - szG_{\rm R}(xL_{\rm NR}(z)z^{-1})} \tag{11}$$

Let σ_θ denote the delay for the θth arrived packet of real-time services. Delay variation is equivalent to the evolution of queue length. We introduce $I(z,x,s) = \sum_{\theta=1}^{\infty} s^{\theta-1} E[z^{\sigma_\theta - \sigma_0} x^{t_\theta}]$ to derive the joint generating function which considers every arrived moment of real-time services packets.

$$I(z,x,s) = \sum_{\theta=1}^{\infty} s^{\theta-1} E[z^{\sigma_\theta-\sigma_0} x^{t_\theta}] = \sum_{\theta=1}^{\infty} s^{\theta-1} E[z^{q_\theta - q_0} x^{t_\theta}] =$$
$$\sum_{\theta=1}^{\infty} s^{\theta-1} \sum_{\delta=0}^{\infty}\sum_{\varepsilon=0}^{\infty} E[z^{q_\theta - q_0} x^{t_\theta} \mid q_0 =$$
$$\delta, q_0^1 = \varepsilon] p(q_0 = \delta, q_0^1 = \varepsilon) =$$
$$\sum_{\delta=0}^{\infty}\sum_{\varepsilon=0}^{\infty}\sum_{\theta=1}^{\infty} s^{\theta-1} z^{-\delta} F_\theta(z,x) p(q_0 = \delta, q_0^1 = \varepsilon) =$$
$$\sum_{\delta=0}^{\infty}\sum_{\varepsilon=0}^{\infty} z^{-\delta} F(z,x,s) p(q_0 = \delta, q_0^1 = \varepsilon) \tag{12}$$

Jitter is the difference of delay, from Eq. (12) we can find that the PGF of jitter is equal to $I(z,1,0)$. We define 0^0=1. Therefore, we have

$$J(z) = E[z^{\sigma_1 - \sigma_0}] = I(z,1,0) =$$
$$\sum_{\delta=0}^{\infty}\sum_{\varepsilon=0}^{\infty} z^{-\delta} z^{\varepsilon+1} L_{\rm NR}^{-1}(z) G_{\rm R}(L_{\rm NR}(z)z^{-1}) p(q_0 = \delta, q_0^1 = \varepsilon) =$$
$$zL_{\rm NR}^{-1}(z) G_{\rm R}(L_{\rm NR}(z)z^{-1}) \sum_{\delta=0}^{\infty}\sum_{\varepsilon=0}^{\infty} z^{-\delta} z^{\varepsilon} p(q_0 = \delta, q_0^1 = \varepsilon) =$$
$$zL_{\rm NR}^{-1}(z) G_{\rm R}(L_{\rm NR}(z)z^{-1}) E[(z^{-1})^{q_0} z^{q_0^1}] =$$
$$zL_{\rm NR}^{-1}(z) G_{\rm R}(L_{\rm NR}(z)z^{-1}) E[(z^{-1}z)^{q_0}] E[z^{l_0^1}] =$$
$$zG_{\rm R}(L_{\rm NR}(z)z^{-1}) \tag{13}$$

We can derive the probability distribution of the jitter of real-time services by the inverse transform [18].

5 Simulations

In this section, first, we present the simulation results of the jitter analysis for real-time services. Then the relationship between jitter and parameters setting of MAC layer are revealed. The jitter varies widely in the choice of the access parameters (macMaxFrameRetries, macMinBE, etc.). The results provide useful insights on optimal parameters setting in random access procedure. All the results are obtained by simulations based on Matlab. In our simulations, we assume that the packet length of real-time services and non-real-time services are fixed and equal to 24 backoff slots and we let $M_{\rm R} = 5, M_{\rm NR} = 10, \quad \lambda_{\rm R} = 0.1$. The value of macMaxCSMABackoffs is 4 and macMaxBE is 5. Let m and n represent macMinBE and macMaxFrameRetries, respectively.

First, the disturbance caused by the non-real-time service as the two types of services pass through the wireless and wired concatenated network is evaluated. Fig. 4 shows the probability distributions of the jitter of real-time services in the scenarios of different arrival rates of non real-time services.

Fig. 4 indicates that the lowest arrival rate of non-real-time services results in the steepest jitter distribution and the highest arrival rate causes the most sluggish one. The jitter distribution becomes more and more sluggish with the increase of $\lambda_{\rm NR}$. The reason is as follows. The collision probability grows with the increase of the arrival rate of non-real-time services, which results in more packets being retransmitted once, twice, or more. Therefore, the randomness of arrival packets of non-real-time services will increase, eventually, the jitter of real-time services will increase. It is demonstrated that jitter is sensitive to the arrival rate of non-real-time services which may seriously affect the service quality for real-time services. Furthermore, whatever the arrival rate of the non-real-time service is, the maximum probability of jitter always appears at 24 backoff slots. This phenomenon depends on the arrival characteristics of the two types of services in IP networks, namely the service processes in IEEE 802.15.4 WSNs. This is due to the fact that we assume that the packet lengths of the two types of services are 24 backoff slots (i.e., one time slot) and each packet requires a single time slot to be served. The peak of jitter distribution changes with the variation of packet length and service rate of IP networks.

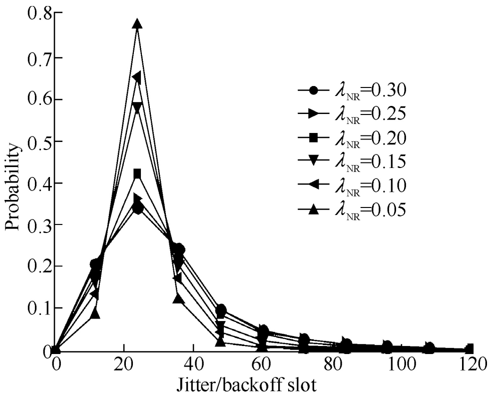

Fig. 4 Probability distributions of jitter with different arrival rates of non-real-time services (m=3 and n=3)

In Figs. 5 and 6, we plot the probability distributions of the jitter for real-time services at the cases of different macMinBE and macMaxFrameRetries. Fig. 5 is plotted by varying the value of macMinBE from 1 to 5. In Fig. 5, it is interesting to observe that the probability distribution of jitter is broader as the macMinBE value becomes larger. The packets with larger macMinBE are likely to wait a time randomly generated in a longer range $[0, 2^m-1]$. That is, with the increase in macMinBE, the duration of backoff increases. The larger the backoff time is, the longer the inter-arrival time of real-time services is, which increases the uncertainty in the number of arrival of non-real-time services packets, therefore, the jitter probability distribution becomes broader.

Fig. 6 presents the jitter probability distributions of real-time services at different macMaxFrameRetries by keeping the same macMinBE and the arrival rate of non-real-time services. From Fig. 6, we can see that the probability distribution of the jitter varies little with the macMaxFrameRetries value increases. Particularly, when the macMaxFrameRetries value is greater than 3, the jitter remains unchanged. This is due to the fact that the maximum number of retries is set to 3 may be sufficient for most packets to be successfully transferred. In addition, comparing Fig. 6 with Fig. 5, we can find that macMaxFrameRetries has very limited impact on jitter feature of real-time services while macMinBE strongly influences the jitter performance of real-time services.

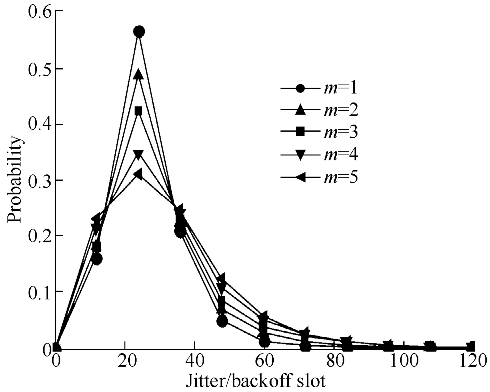

Fig. 5 Probability distributions of jitter with different macMinBE (λ_{NR} = 0.2 and n=3)

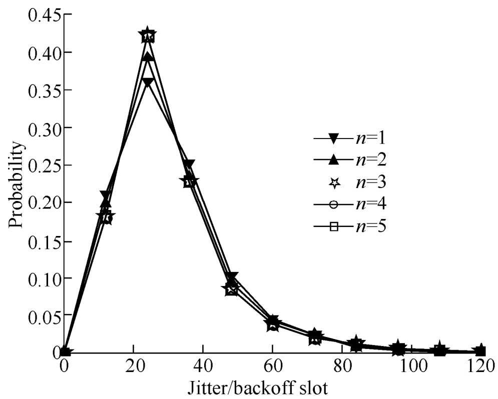

Fig. 6 Probability distributions of jitter with different macMaxFrameRetries (λ_{NR} = 0.2 and m=3)

In Figs. 7 and 8, we plot the average jitter of real-time services by TAM and steady-state analysis methods (SAM), respectively. From Figs. 7 and 8, we can observe that the values of average jitter have the same changing tendency by the two methods. In addition, the value of average jitter by utilizing the SAM always higher than the value by using TAM. This is due to the difference of the two types of jitter definitions. Steady-state analysis methods can only get the average jitter, however, based on transient analysis methods, we can obtain the probability distribution of the jitter which can describe the characteristics of jitter more accurately.

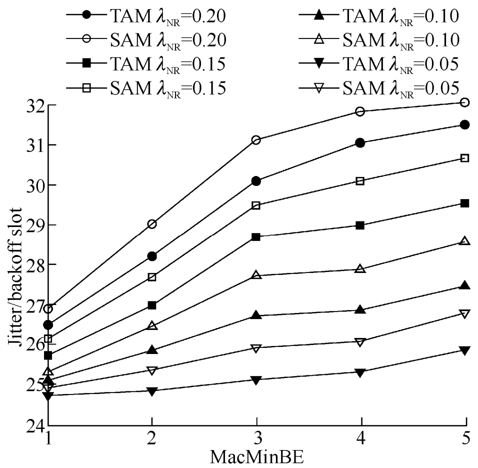

Fig. 7 Jitter with respect to macMinBE and λ_{NR} (n=3)

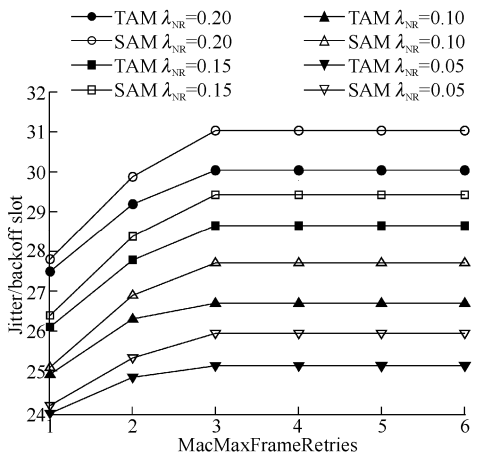

Fig. 8 Jitter with respect to macMaxFrameRetries and λ_{NR} (m=3)

Fig. 7 presents how macMinBE and λ_{NR} influence the jitter of real-time services. From Fig. 7, we can find that the jitter increases monotonically as macMinBE value increases. The growth in macMinBE leads to the fact that the transmission attempts of different terminals are spread over a larger time range. Therefore, the time interval between adjacent packets of the real-time service gets larger and the nondeterminacy of the arrival of non-real-time services packets increases accordingly, which results in the bigger jitter. A simple corollary is that the lower jitter can be obtained by setting the smaller value of macMinBE.

Fig. 8 describes the impacts of parameter macMaxFrameRetries and λ_{NR} on jitter. It is demonstrated that when the value of macMaxFrameRetries is greater than 3, the jitter is constant irrespective of the macMaxFrameRetries value. This characteristic is attributed to the fact that for the small values of macMaxFrameRetries, the increase in macMaxFrame-Retries can significantly increase the duration of retransmission which increases the inter-arrival time of real-time services, therefore, the jitter becomes larger. However, for the bigger values of macMaxFrameRetries, the augment in the inter-arrival time of real-time services becomes less significant, therefore, the jitter remains unchanged. From Figs. 7 and 8, we also find that the larger the arrival rate of non-real-time services is, the larger the jitter is.

From the analyses presented in Sect. 4, we find that the jitter depends on the inter-arrival time of real-time services and the number of non-real-time services packets waiting to be served in the queue. When the values of macMinBE and macMaxFrameRetries increase, the packet loss rate may decrease, however, the jitter increases. This characteristic provides some references for optimal parameters setting in random access procedure.

6 Conclusions

In this paper, we have investigated the jitter of real-time services which was affected by the stochastic arrivals of non-real-time services in wireless (IEEE 802.15.4 WSNs) and wired (IP core networks) concatenated networks. For the IEEE 802.15.4 WSNs, we have deduced the packet departure process which in turn is the arrival process of the IP core network. With the help of the transient analysis method, we have analyzed the dynamic queuing system evolving on a dynamic time interval. Further, we have explored the relationship between the jitter of real-time services and the variation in queue length. Jitter distribution of the real-time service has been derived. The analysis and simulation results indicated that jitter is tightly connected with the parameters setting of the access procedure in IEEE 802.15.4. In addition, the arrival rate of non-real-time services has a great impact on the jitter of real-time services. The larger the arrival rate is, the bigger the jitter is. In the future, it is an interesting topic to explore the performance of the jitter in the scenario that the contention access and the time division multiple access (TDMA) are jointly considered as well as the multi-router IP networks.

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