On the Stability of Random Access with Congestion Control

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Abstract. The random access protocol is a critical technique widely used in various wireless networks. A significant challenge is analyzing the stability of the random access system when a large number of users transmit packets independently. Although the congestion control policy can enhance the stability of the system, there is currently a lack of quantitative analysis on the stability of random access with congestion control. In this paper, we analyze the random access system with congestion control and quantify its stability. Specifically, we consider a congestion control scheme to enhance the stability of the random access system and present the graphical analytical model. Based on this graphical model, we qualitatively discuss the behavioral variations of the system as it works and quantify its stability.

Keywords: Random access · Slotted ALOHA · Retransmission policy · Congestion control · Stability analysis

1 Introduction

The random access protocol is a critical technique widely used in various wireless networks. Among them, slotted ALOHA [1] enjoys high popularity. In slotted ALOHA systems, users share a channel without coordination, which can lead to signal collisions. Due to signal collisions resulting from two or more users accessing the channel simultaneously, the peak throughput of a slotted ALOHA system is limited to 0.37. Numerous studies focus on enhancing the throughput performance of slotted ALOHA systems, which determines the allowable number of users accessing wireless networks. Based on slotted ALOHA, the study in [2] proposes diversity slotted ALOHA (DSA) to enhance throughput performance, which only outperforms slotted ALOHA slightly at low normalized

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loads. A breakthrough in random access is contention resolution diversity slotted ALOHA (CRDSA) [3], which combines diversity transmission with successive interference cancellation (SIC) to enhance throughput performance. Specifically, each user repeatedly transmits a packet over a medium access control (MAC) frame. The receiver attempts to decode the non-collision packets and subtracts the decoded packets from the slots in which their copies are located. Based on CRDSA, [4] introduces irregular repetition slotted ALOHA (IRSA). In contrast to CRDSA, where the packet repetition rate is the same for all users, in IRSA, the packet repetition rate is chosen according to an optimized probability distribution. Additionally, coded slotted ALOHA (CSA) is proposed in [5], where users utilize erasure-correcting codes on packet segments instead of directly repeating the packet, and then transmit the encoded packet segments in the shared channel. In [6], it is proven that the throughput of the SIC-based ALOHA scheme can be arbitrarily close to 1 in the asymptotic frame size setting, which is the upper bound on performance without considering the capture effect and multiple user detection techniques.

In addition to enhancing throughput performance, another crucial aspect of the research on random access is analyzing the stability of the system. In general random access research, it is commonly assumed that for a given channel traffic, an equilibrium point is reached where the average number of packet transmissions is equal to the average number of successful packet transmissions. However, when considering the number of previous unsuccessful retransmissions, the random access system becomes inherently unstable. Actually, the retransmission policy is a key element in ensuring the reliability of data transmission in most wireless networks [7]. Only a few studies concentrate on analyzing the stability of the random access system with a retransmission policy. [8,9] formulate the mathematical analytical model for the slotted ALOHA system with a retransmission policy and discuss its stability, respectively. Following this, [10,11] extend the analytical model and method presented in [8,9] to the CRDSA system, respectively. Furthermore, [12] investigates the stability of an asynchronous random access system by adopting the analytical model in [9]. On the other hand, to enhance the stability of the random access system, [13] proposes several congestion control schemes to prevent the system from becoming unstable, and [14] applies these congestion control schemes to the CRDSA system. However, the current research on the stability of random access with congestion control focuses on qualitatively discussing the behavioral variations of the system, especially in terms of throughput and delay performance. There is a lack of quantitative analysis on the stability of random access with congestion control, which is crucial for calculating the maximum allowable number of accessing users and measuring the performance improvement of the congestion control scheme.

To bridge this gap, in this paper, we analyze the random access system with congestion control and quantify its stability. We initially analyze the stability of several uncontrolled random access systems and discuss their limitations. Subsequently, we consider a congestion control scheme to enhance the stability of the system and present the graphical analytical model. Based on this graphical model, we qualitatively discuss the behavioral variations of the system as it works and quantify its stability.

The rest of this paper is organized as follows: In Sect. 2, we provide a brief review of the SIC-based ALOHA scheme. Section 3 analyzes the stability of several uncontrolled random access systems. In Sect. 4, a congestion control scheme and the corresponding graphical analytical model are presented. In Sect. 5, we analyze the stability of random access with congestion control qualitatively and quantitatively based on the graphical analytical model. This paper concludes in Sect. 6.

2 Review of SIC-Based ALOHA Scheme

In this section, we briefly review the SIC-based ALOHA scheme, which represents the current advanced random access schemes, and analyze its stability later. More details and relative performance analysis can be referred to [3,4]. When transmitting, we consider the time division multiple access (TDMA) scheme, where the transmission period is a TDMA frame, and each TDMA frame consists of n slots with the same duration. In each TDMA frame, the number of active users is denoted by m. Each active user attempts to transmit a packet and makes only one transmission, which means no retransmission occurs within the same TDMA frame. The packet duration is equal to the slot duration if guard time is neglected, and the packets keep slot synchronization. The normalized channel traffic G is defined as $G = m/n$ and represents the average number of packet transmissions per slot. The normalized throughput T is the average number of successful packet transmissions per slot.

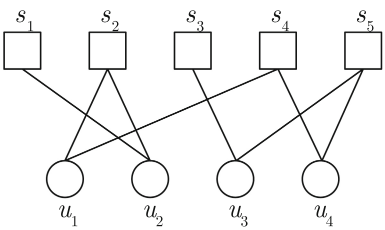


Fig. 1. The bipartite graph representation of a random access process within a TDMA frame, where $m = 4$, $n = 5$, and $l = 2$ for all users.

In the SIC-based ALOHA scheme, each user appends a pointer to the data payload to create a packet. When transmitting, each user creates l packet copies and transmits them over l slots selected randomly from the n slots within a TDMA frame, where l is a design parameter denoting the packet repetition rate. The pointer serves the function of indicating the slots where the other copies are located. For CRDSA, the packet repetition rate is the same for all users, while for IRSA, the packet repetition rate is determined according to an optimized probability distribution termed the degree distribution. According to [4], it is beneficial to represent the random access process within a TDMA frame using a bipartite graph. Figure 1 depicts the bipartite graph representation of an example random access process. The circular nodes are user nodes whose packets need recovery, while the square nodes are slot nodes indicating the received signals in corresponding slots. If user k transmits a packet copy in the jth slot, it creates an edge between u_k and s_j.

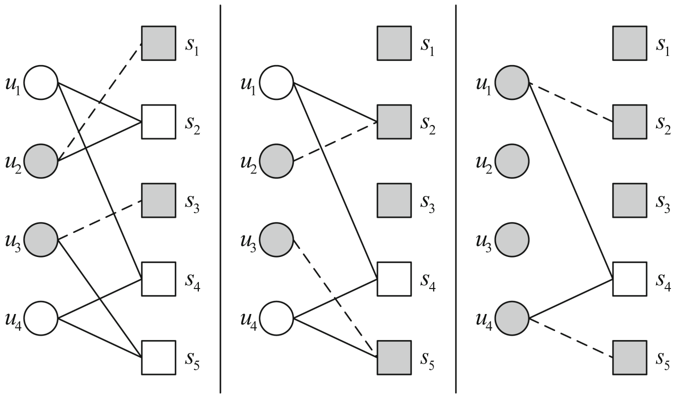


Fig. 2. The bipartite graph representation of the SIC decoding process.

Whenever a packet copy is detected and successfully decoded in a collision-free slot, the receiver reconstructs and subtracts the interference signal in the slots where the other copies are located according to the embedded pointer using the SIC decoding algorithm. As a result, the collision slots may be transformed into collision-free slots, allowing for successful decoding of packet copies from other users in these slots. The SIC decoding algorithm is performed iteratively until no collision-free slots remain. The bipartite graph representation of the SIC decoding process is shown in Fig. 2. Specifically, s_1 and s_3 are collision-free slots where the packet copies of u_2 and u_3 are detected and successfully decoded. The receiver reconstructs and subtracts the interference signals of u_2 and u_3 in s_2 and s_5, respectively. Consequently, s_2 and s_5 are converted into collision-free slots, and the packet copies of u_1 and u_4 can also be detected and successfully decoded.

Figure 3 presents a normalized throughput performance comparison for various random access schemes, where $n = 100$ and the degree distribution of IRSA is $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$ [4]. As depicted in Fig. 3, all performance curves exhibit a trend of increasing and then decreasing as G increases. Hence, there exists a peak throughput for each random access scheme, denoted as T_p. As G increases, when T exceeds T_p, the larger the T_p, the more sharply T descends. However, in the following section, we will discuss that the system may actually

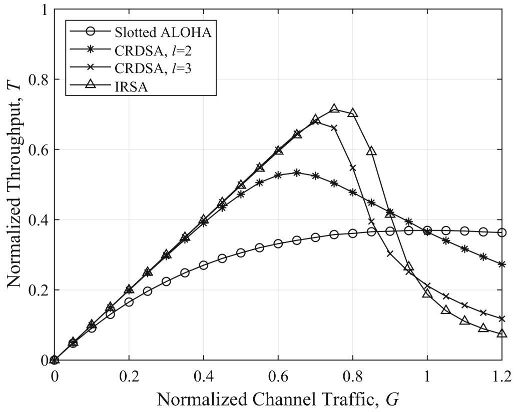


Fig. 3. Normalized throughput performance comparison for various random access schemes.

fail to achieve the theoretical peak throughput of the random access scheme when considering the previous unsuccessful retransmissions, which may lead to system congestion.

3 Stability Analysis for Uncontrolled Random Access Systems

In this section, we analyze the stability of several uncontrolled random access systems and discuss their limitations. Our analysis is based on a graphical representation of the random access process similar to that in [9,11]. However, we specifically focus on the traffic model involving an infinite population, which is closer to the real application scenario where a large number of users transmit packets independently, regardless of whether previous transmissions are still pending or not. Figure 4 depicts the graphical model for the uncontrolled random access system with a retransmission policy within a TDMA frame. Defining:

N_A^f: the number of newly arrived active users in the fth frame, which is a Poisson random variable with parameter λ, i.e., $N_A^f \sim Poisson(\lambda)$

N_B^f: the number of backlogged users whose packets were unsuccessfully received in the fth frame

$G_T^f = N_A^f/n$: the normalized channel traffic coming from the packet transmissions of the newly arrived active users in the fth frame

$G_B^f = N_B^{(f-1)}/n$: the normalized channel traffic coming from the packet retransmissions of the backlogged users in the fth frame

$G_{IN}^f = G_T^f + G_B^f$: the sum normalized channel traffic in the fth frame

$T^f = G_{IN}^f \left(1 - plr(G_{IN}^f, n)\right)$: the normalized throughput in the fth frame, where $plr(\cdot)$ is the packet loss rate of the random access scheme.

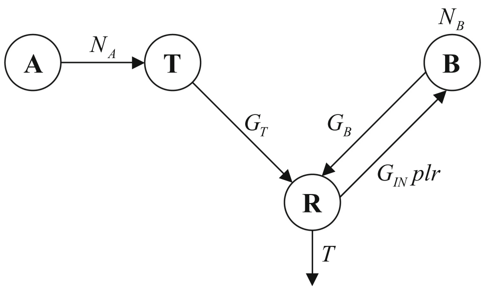


Fig. 4. Graphical model for the uncontrolled random access system with a retransmission policy.

When the random access system works in a stable state, we have

$$G_T = T = G_{IN} \cdot (1 - plr\,(G_{IN}, n)), \tag{1}$$

and

$$N_B = G_{IN} \cdot plr\,(G_{IN}, n) \cdot n, \tag{2}$$

where the superscript f is omitted, which means that in each frame, the newly offered channel traffic should be approximately equal to the throughput, and the number of backlogged users should remain constant dynamically. Equations (1) and (2) completely describe the equilibrium contour on the (G_T, N_B) plane, which is proposed in [9,11] to analyze the behavioral variations of the system. Since the number of newly arrived active users in each frame can be modeled as a Poisson random variable with parameter λ, the channel load line is defined as

$$G_T = \frac{\lambda}{n}, \tag{3}$$

which means that the newly offered channel traffic is constant and independent of the number of backlogged users.

Figure 5 depicts the equilibrium contours for various random access schemes and the channel load line, where $n = 100$, $\lambda = 45$, and the degree distribution of IRSA is set to $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$. Here, we simply cite the conclusion regarding the relationship between the stability of the random access system and the equilibrium contour, and a more detailed analysis can be found in [9,11]. As can be seen from the figure, the channel load line and each equilibrium contour may have one, two, or no intersection points. If the number of intersection points is one or zero, the random access system is unstable, whereas if the number of intersection points is two, the random access system is locally stable. Specifically, we assume that there are two intersection points between the channel load line and an equilibrium contour, denoted as N_B^S and N_B^U, where $N_B^U > N_B^S$. When N_B, the number of backlogged users, satisfies $0 \le N_B < N_B^U$, it shows a tendency to converge to N_B^S as the system works, indicating that N_B^S

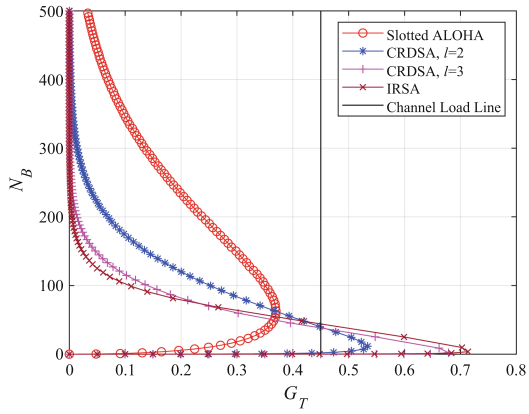
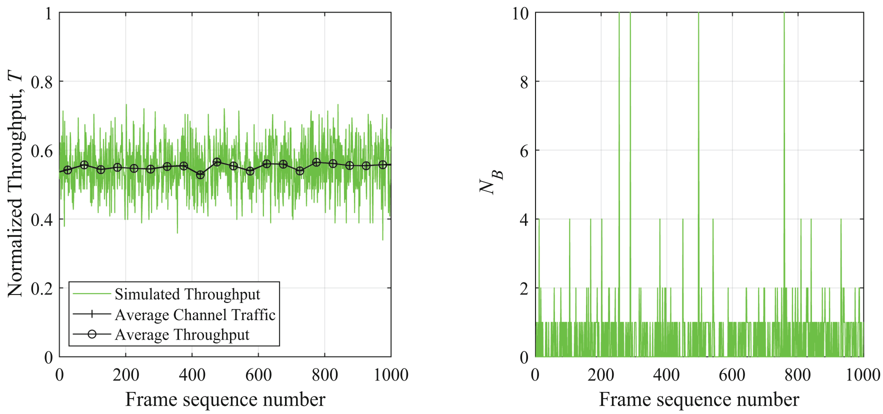


Fig. 5. Equilibrium contours for various random access schemes.

is a locally stable equilibrium point. Once $N_B \geq N_B^U$ due to statistical variations, N_B will increase to infinity as the system works, thus N_B^U is an unstable equilibrium point. Consequently, the random access system is locally stable.

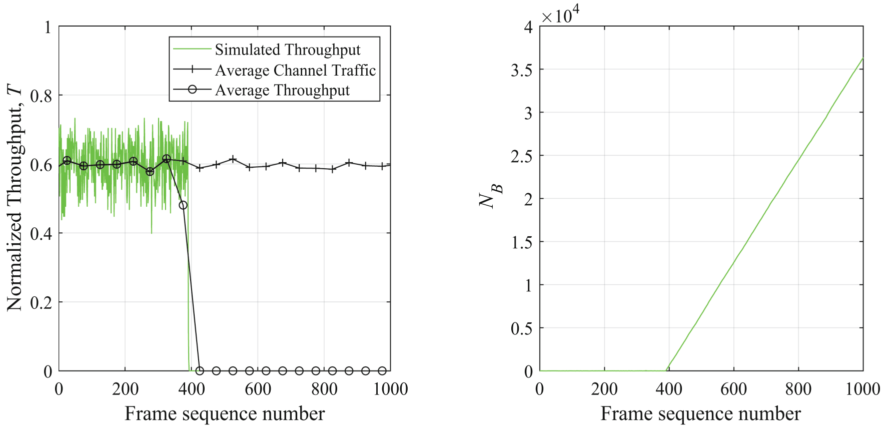
To illustrate the essence of system stability, Fig. 6 depicts the variation trends of the normalized throughput and the number of backlogged users as the system works in a stable state for IRSA, respectively, where $n = 100$, $\lambda = 55$, and the degree distribution of IRSA is set to $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$. As can be seen from the figure, the average offered channel traffic is approximately equal to the average throughput, and the number of backlogged users remains constant in each frame dynamically, consistent with the previous description. Moreover,



(a) The normalized throughput (b) The number of backlogged users

Fig. 6. The variation trends of the performance metrics as the system works for IRSA with $\lambda = 55$ (stable state).

the simulated throughput and the number of backlogged users in each frame fluctuate around a certain value as the system works, respectively. Theoretically, the values correspond to the locally stable equilibrium point N_B^S in Fig. 5.



(a) The normalized throughput (b) The number of backlogged users

Fig. 7. The variation trends of the performance metrics as the system works for IRSA with $\lambda = 60$ (unstable state).

For comparison, Fig. 7 presents the variation trends of the same performance metrics as the system works with $\lambda = 60$. However, what differs from Fig. 6 is that at a specific moment, the number of backlogged users, N_B, exceeds the unstable equilibrium point N_B^U due to statistical variations, leading to system congestion and thus nonfunctional. In this case, the throughput rapidly converges to zero, and the number of backlogged users increases infinitely as the system works. As discussed in the analysis of the simulation results shown in Fig. 3, if the offered channel traffic exceeds the threshold at which the system achieves peak throughput, the throughput will decrease sharply, resulting in a rapid increase in the number of backlogged users. The increase in the number of backlogged users, in turn, causes the offered channel traffic to exceed the threshold again, leading to a vicious cycle that results in system congestion.

It is obvious that the probability of the random access system becoming unstable increases as λ rises. To quantify stability, [9] proposes the concept of average first exit time (FET), defined as the average time that a random access system takes from startup to being in an unstable state. Apparently, the longer the average FET is taken, the more stable the random access system works. Figure 8 compares the average FET for various random access schemes, where $n = 100$. Combined with the simulation results shown in Fig. 3, it can be seen that the higher the peak throughput performance of the random access scheme, the greater its stability. Moreover, taking IRSA as an example, the maximum

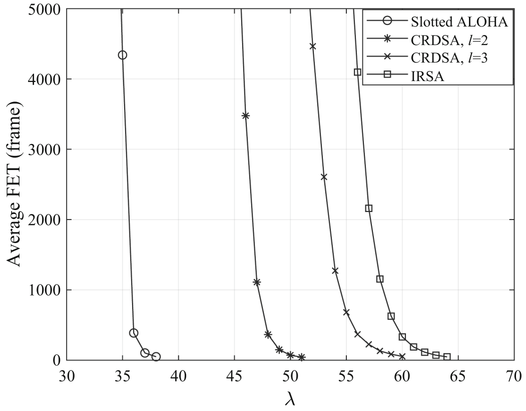


Fig. 8. Average FET for various random access schemes.

allowable average number of accessing users is $\lambda = 55$ to achieve the target average FET of 5000 frames. When λ exceeds this value, the stability of the random access system decreases rapidly. In this case, the achievable maximum normalized throughput of the system is approximately $T = 0.55$, which has a significant gap with the theoretical peak throughput of IRSA in Fig. 3. Consequently, to ensure system stability in light of previous unsuccessful retransmissions, it is essential to restrict the maximum average number of accessing users to a relatively lower value, thus preventing the system from achieving the theoretical peak throughput performance of the random access scheme.

4 The Congestion Control Scheme

In this section, we consider a congestion control scheme to enhance the stability of the random access system and present the corresponding graphical analytical model. The congestion control scheme operates by controlling the access probability for active users. Despite its simplicity, it has proven to be highly effective in practice. The random access process with congestion control is depicted in Fig. 9.

In Fig. 9, for a newly arrived active user with a packet to transmit, the first step is to determine whether the packet is permitted for transmission in the current frame according to the congestion control policy. Specifically, the receiver calculates the control factor, denoted as p_c, based on the estimation of the current number of active users, where $0 \leq p_c \leq 1$. Subsequently, the receiver broadcasts the calculated control factor to all active users over the downlink broadcast channel. Each active user independently generates a random number between 0 and 1 and compares it with the received control factor p_c. If the random number is smaller than p_c, the user is permitted to transmit the packet in the current frame; otherwise, the user needs to wait until the next frame to repeat the aforementioned process.

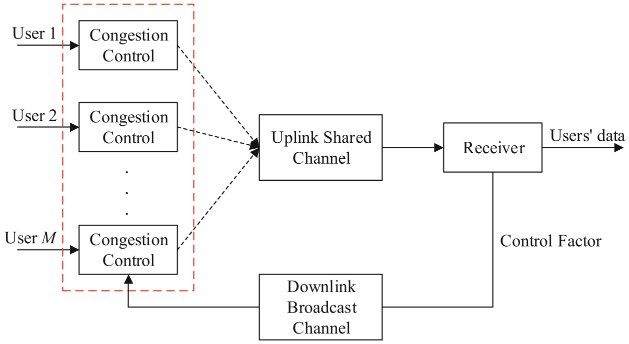


Fig. 9. The random access process with congestion control.

A critical point in designing the congestion control policy is the calculation of the control factor p_c. In the considered congestion control scheme, the control factor is calculated as

$$p_c = \min\left(1, \frac{G^* n}{\hat{M}}\right), \tag{4}$$

where G^* is the threshold of the offered channel traffic at which the system achieves peak throughput of the random access scheme, n is the number of slots contained in a TDMA frame, and $\hat{M}$ is the estimated number of active users in the current frame at the receiver. To simplify the analysis, we assume a perfect estimation of the number of active users at the receiver. It is designed so that when the offered channel traffic exceeds the corresponding threshold of the random access scheme, the expected average channel traffic is controlled to G^*.

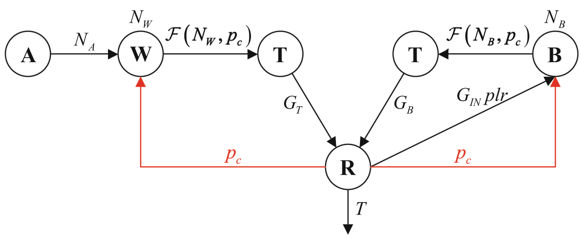


Fig. 10. Graphical model for the random access system with congestion control.

To analyze stability, Fig. 10 presents the graphical model for the random access system with congestion control, defining:

N_A^f: the number of newly arrived active users in the fth frame, which is a Poisson random variable with parameter λ, i.e., $N_A^f \sim Poisson(\lambda)$

$N_W^f = N_W^{(f-1)} - \mathcal{F}\left(N_W^{(f-1)}, p_c^{(f-1)}\right) + N_A^f$: the number of active users in a waiting state in the fth frame, each with a packet to transmit, including both the newly arrived active users and those who were previously prohibited from transmitting the packet due to the congestion control policy. $\mathcal{F}\left(N_W^f, p_c^f\right)$ denotes the number of active users in a waiting state permitted to transmit the packet in the fth frame

N_B^f: the number of backlogged users whose packets were unsuccessfully received in the fth frame and previous frames

p_c^f: the control factor in the fth frame, calculated by the receiver according to (4)

$G_T^f = \mathcal{F}\left(N_W^f, p_c^f\right)/n$: the normalized channel traffic coming from the packet transmissions by some of the active users in a waiting state in the fth frame

$G_B^f = \mathcal{F}\left(N_B^{(f-1)}, p_c^f\right)/n$: the normalized channel traffic coming from the packet retransmissions by some of the backlogged users in the fth frame

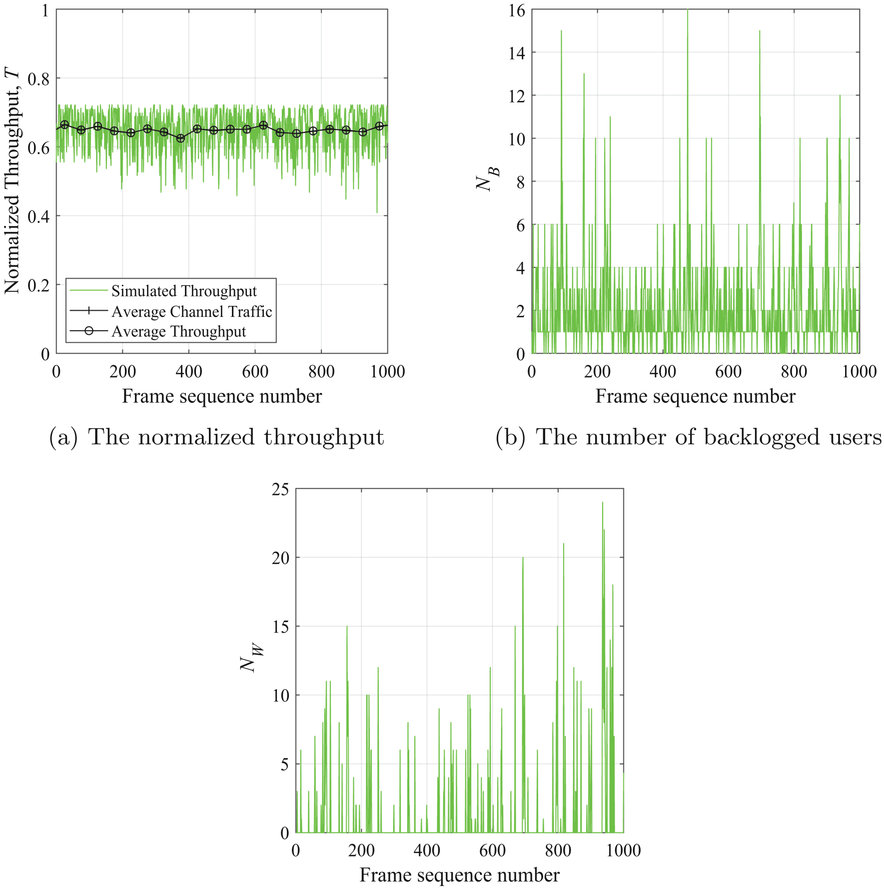
$G_{IN}^f = G_T^f + G_B^f$: the sum normalized channel traffic in the fth frame

$T^f = G_{IN}^f\left(1 - plr(G_{IN}^f, n)\right)$: the normalized throughput in the fth frame, where $plr(\cdot)$ is the packet loss rate of the random access scheme.

5 Simulation Results

In this section, we analyze the stability of the random access system with congestion control based on the graphical model in Fig. 10. Figure 11 presents the variation trends of the relevant performance metrics as the system works in a stable state for IRSA with congestion control, where $n = 100$, $\lambda = 65$, and the degree distribution of IRSA is set to $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$. It can be seen that the variation trends in Fig. 11 exhibit some similarities with those in Fig. 6. Specifically, the average offered channel traffic is approximately equal to the average throughput. In contrast, the number of backlogged users fluctuates more sharply around a certain value compared to that in Fig. 6. As for the number of users in a waiting state, it varies dynamically but remains finite.

However, as λ continues to increase, the random access system with congestion control will eventually become unstable. To this end, Fig. 12 presents the variation trends of the same performance metrics as the system works for IRSA with congestion control in the case of $\lambda = 68$, which is the average number of accessing users that can lead to the system becoming unstable with high probability. In contrast to those shown in Fig. 7, when the average offered channel traffic is not equal to the average throughput due to statistical variations, indicating that the system becomes unstable, the throughput of the IRSA system with congestion control does not tend to 0, but instead fluctuates dynamically around a relatively lower value. However, since the average offered channel traffic exceeds the average throughput, both the number of backlogged users and the number of users in a waiting state grow infinitely, but the number of backlogged

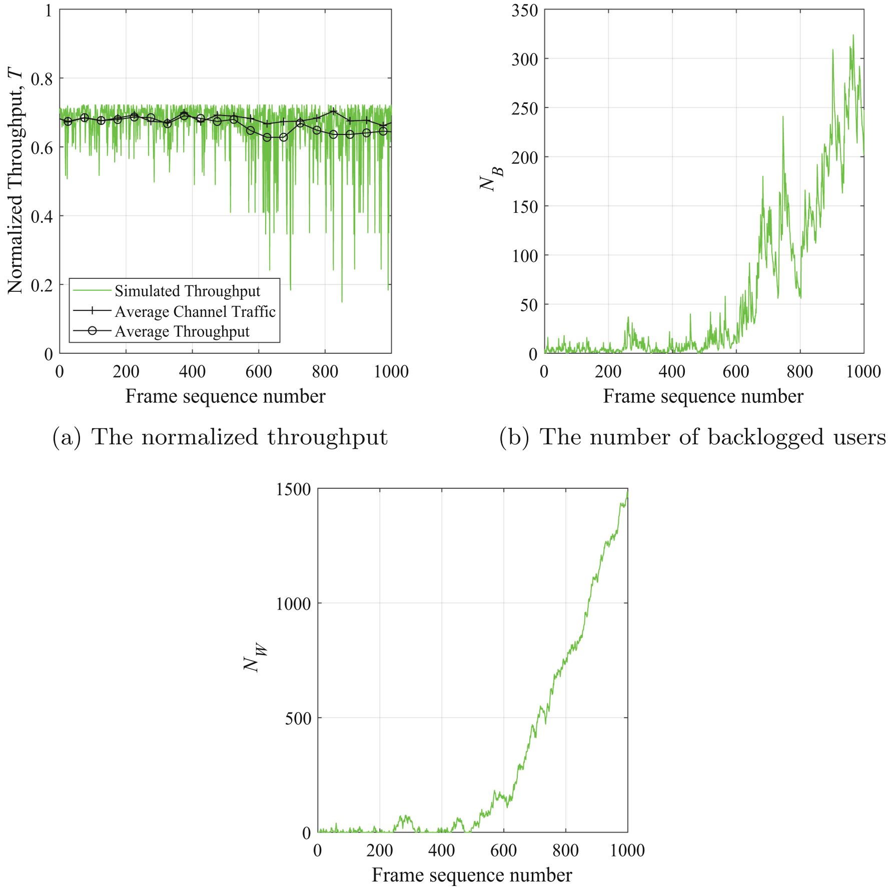


(c) The number of users in a waiting state

Fig. 11. The variation trends of the performance metrics as the system works for IRSA with congestion control (stable state), $\lambda = 65$.

users increases much more slowly compared to that in the uncontrolled system shown in Fig. 7.

To measure the performance improvement of the congestion control scheme, it is essential to quantify the stability of a random access system with congestion control. However, the calculation algorithm for FET proposed in [9], which is based on calculating the probability that the number of backlogged users exceeds the unstable equilibrium point, can only be applied in the case of the uncontrolled random access system. According to the simulation results shown in Fig. 11 and Fig. 12, it can be seen that the number of users in a waiting state, N_W, reflects the state of the system more accurately since the variation of the number of backlogged users fluctuates sharply. Therefore, we can define a threshold for N_W, denoted as $\bar{N}_W$. Once N_W exceeds the defined threshold $\bar{N}_W$



(a) The normalized throughput

(b) The number of backlogged users

(c) The number of users in a waiting state

Fig. 12. The variation trends of the performance metrics as the system works for IRSA with congestion control (unstable state), $\lambda = 68$.

as the system works, it signifies that the system is beginning to be in an unstable state. Based on this, Fig. 13 depicts the average FET for various random access schemes with and without congestion control (congestion control is denoted as "CC" in Fig. 13), where $n = 100$, $\bar{N}_W = 200$, and the degree distribution of IRSA is set to $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$. As can be seen from the figure, to achieve the target of an average FET of 5000 frames in the uncontrolled random access system, the maximum allowable average number of accessing users is $\lambda = 45$, 51, and 55 for CRDSA with $l = 2$, CRDSA with $l = 3$, and IRSA, respectively. While for random access systems with congestion control, the maximum allowable average number of accessing users is increased to $\lambda = 51$, 63, and 66 for CRDSA with $l = 2$, CRDSA with $l = 3$, and IRSA, resulting in performance improvements of 13.3%, 23.5%, and 20%, respectively. It can be seen that the

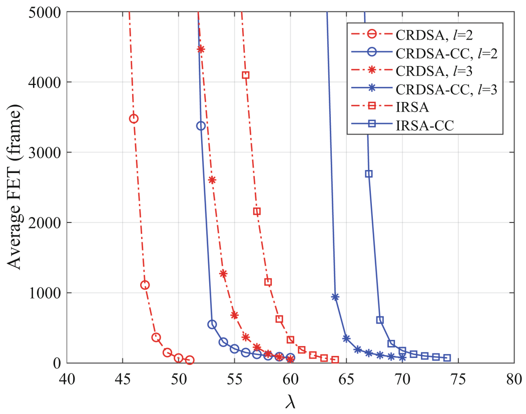


Fig. 13. Average FET for various random access schemes with and without congestion control.

congestion control scheme can notably enhance the stability of random access systems, thereby improving their throughput performance.

6 Conclusions

Quantifying the stability of random access with congestion control is crucial, especially when a large number of users transmit packets independently, for calculating the maximum allowable number of accessing users and measuring the performance improvement of the congestion control scheme. In this paper, we analyzed the stability of various uncontrolled random access systems and discussed their limitations. Based on this, we considered a congestion control scheme to enhance stability and presented the corresponding graphical analytical model. Finally, we qualitatively explored the behavioral variations of the system with congestion control as it works and quantified its stability through the graphical model.

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