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PERFORMANCE OF ALOHA-Q WITH ADAPTIVE TRANSMISSION PROBABILITY

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ABSTRACT

We propose incorporation of adaptive transmission probability to ALOHA-Q, which is a framed slotted ALOHA-based random access protocol ingeniously integrating Q-learning for slot selection in a frame. The transmission probability is also adaptively controlled based on Q-learning. Performance of the proposed protocol is confirmed by means of computer simulation. Numerical results show that the proposed protocol can mitigate performance degradation of ALOHA-Q under overloaded traffic condition and exhibits comparable performance to ALOHA-Q for moderate traffic condition.

KEYWORDS

Framed Slotted ALOHA, Q-Learning, ALOHA-Q, Throughput, Transmission Probability

1. INTRODUCTION

Recent spread of tiny Internet-of-Things (IoT) devices and Machine-to-Machine (M2M) devices facilitates the rapid increase in burst traffic [1]. An application range of such devices includes not only terrestrial communication networks and body area networks [2], [3] but also satellite communication networks [4], underwater sensor networks [5], and hybrid configurations of the above networks. In order to accommodate the ceaseless growth of communication demand within limited bandwidth, access control protocols play an important role.

Random access protocols originated from the well-known ALOHA protocol in 1970 [6]. ALOHA-based random access protocols have been favorably implemented due to their simplicity in numerous communication systems [1], [4], [7], [8],[9],[10]. In RFID systems [7], a dynamic FSA (Framed Slotted ALOHA) [11] is utilized for the anti-collision algorithm. In [8], [10], the use of ALOHA-Q [12], which is an ingenious integration of FSA and Q-learning, is proposed for underwater network design, and the performance is evaluated. In [9], the use of ALOHA-Q is considered in the scenario where immediate acknowledgements are unavailable. ALOHA-Q offers good performance, since Q-learning endeavors to achieve a TDMA-like convergence of slot assignment in a frame [8],[9], [10]. Within the framework of ALOHA-Q, most of the literatures assume that the frame length be equal to the number of possible active nodes [8], [9]. However, it is easy to conjecture that the performance of ALOHA-Q is degraded under overloaded traffic conditions, where the number of active nodes at the beginning of a frame exceeds the frame length in the slot.

In this paper, we propose incorporation of transmission probability to ALOHA-Q in order to mitigate overloaded traffic condition. The transmission probability is also adaptively controlled based on Q-learning. Performance of the proposed protocol is evaluated by means of exhaustive computer simulation in terms of throughput, packet collision probability and Jain's fairness index [13].

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The rest of the letter is organized as follows: Section II presents a system model and describes FSA. ALOHA-Q is briefly reviewed in Section III. In Section IV, we propose the incorporation of transmission probability with ALOHA-Q. Numerical results obtained by means of computer simulation are presented in Section V. Finally, Section VI concludes the present letter.

2. SYSTEM MODEL AND FRAMED SLOTTED ALOHA

Consider a random access network with N single-buffer nodes contending for a common receiver through a shared channel. The time axis is divided into slots of unit length. A node with an empty buffer generates a new packet of unit length with probability λ at the beginning of each time slot. It follows from the single-buffer assumption that a node with an occupied buffer generates no new packets. Furthermore, L consecutive slots construct a frame. We assume ideal slot- and frame-synchronizations in the network. A packet transmission results in success, if no other simultaneous packet transmissions occur. We ignore channel noise and fading. On the other hand, packet collision happens and all the packets in collision must be retransmitted in a properly selected slot afterward, so that we ignore the capture effect [14].

In FSA, a node with packet at the beginning of a frame; active node, transmits the packet in a slot randomly selected among L slots in frame. If packet transmission fails, the node randomly selects one slot in the next frame and retransmits the packet until packet transmission succeeds.

3. ALOHA-Q

As shown in [6], the frame length Lin FSA should be dynamically adjusted according to the number of active nodes at the beginning of the frame, in order to maximize the throughput. However, it is complicated to obtain or approximate the number of such nodes in real-time. Instead, an introduction of an effective tool from a framework of reinforcement learning facilitates the performance improvement of FSA without adjusting the frame length. ALOHA-Q [8],[9],[10],[12] incorporates FSA with Q-learning. In ALOHA-Q, each node equips an L-dimensional vector, which is referred to as a Q-table;

$$\boldsymbol{Q}_t = \left[q_{t,1}, q_{t,2}, \cdots, q_{t,L}\right] \qquad (1)$$

where $q_{t,\ell}$ is a real number; $\ell = 1, 2, \cdots, L$, t is the frame number; $t = 1, 2, \cdots$, and the initial condition is $\boldsymbol{Q}_1 = \boldsymbol{0}$. An active node transmits a packet in Slot i with the maximum $q_{t,i}$, where $i = \arg\max_\ell [q_{t,\ell}]$. If there exist two or more such slot numbers, $i$is randomly selected among them. Then, the value of $q_{t,i}$ is updated for the next frame depending on the outcome of the packet transmission, success or unsuccessful, as follows [8],[9],[10],[12];

$$q_{t+1,i} = q_{t,i} + \alpha\left(r_t - q_{t,i}\right) = (1-\alpha)q_{t,i} + \alpha r_t, \qquad (2)$$

where $\alpha$is the learning rate, $0 \leq \alpha \leq 1$, and r_t is the reward at Frame t;

$$r_t = \begin{cases} R_{\text{succ}}, & \text{for successful transmission,} \\ R_{\text{fail}}, & \text{for unsuccesful transmission.} \end{cases} \qquad (3)$$

It follows from (2) that the updated value $q_{t+1,i}$ is an internally dividing point between $q_{t,i}$and r_t at ratio of $\alpha : (1-\alpha)$. Therefore, large α may lead to drastic and unstable change of the value of $q_{t,i}$. Note that the value of$q_{t,\ell}$is unchanged for Slot $\ell \neq i$ with no packet (re)transmission.

[Example 1] A simple example of ALOHA-Q is shown in Figure 1 for $N = L = 3$, $\alpha = 0.5$, $R_{\mathrm{succ}} = 1.0$ and $R_{\mathrm{fail}} = -1.0$. Suppose that at Frame 1, Nodes 1 and 2 have their own packet and Node 3 has no packet to transmit. Nodes 1 and 2 randomly select Slot 1 and 2 for packet transmission, respectively, since $\boldsymbol{Q}_1 = \boldsymbol{0}$. Both packet transmissions are successful, then the corresponding value is updated as $q_{2,1} = \alpha = 0.1$ at Node 1 and$q_{2,2} = 0.1$ at Node 2. At Frame 2, Nodes 1 and 2 transmit their next packet in a slot with the maximum value in their Q-table. On the other hand, Node 3 randomly select a slot for packet transmission. Since two packets collide in Slot 1, Nodes 1 and 3 updates their Q-table as $q_{3,1} = (1-\alpha)q_{2,1} - \alpha = -0.01$ at Node 1 and $q_{3,1} = -\alpha = -0.1$ at Node 3. Successful Node 2 increases its $q_{2,2} = 0.1$ to $q_{3,2} = (1-\alpha)q_{2,2} + \alpha = 0.19$.

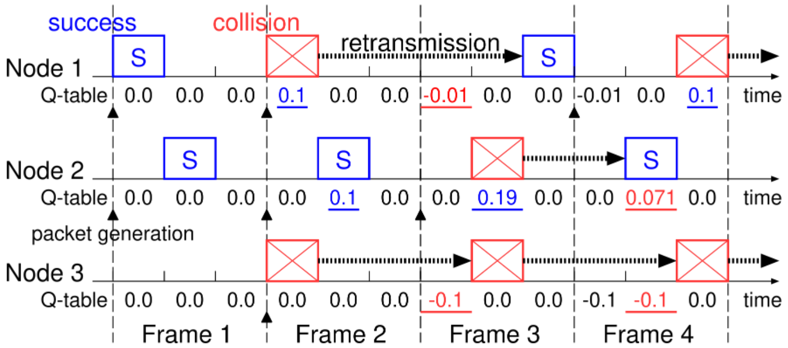


Figure 1. Example of ALOHA-Q for $N = L = 3$, $\alpha = 0.5$, $R_{\mathrm{succ}} = 1.0$and $R_{\mathrm{fail}} = -1.0$.

4. INTRODUCING ADAPTIVE TRANSMISSION PROBABILITY

It is known in [8], [10], [12] that ALOHA-Q can successfully manage slot assignment in a frame to each node when the number of nodes is equal to the frame length and each node is saturated, that is, for the case of $N = L$ and $\lambda = 1.0$. However, inthe case that the number of active nodes is greater than the frame length and that a node is nearly saturated, packet collisions tend to occur in a number of slots in a frame, since an active node at the beginning of a frame inevitably transmits its packet, even if Q-learning is incorporated.

In order to avoid packet collision in such a case, we propose to introduce adaptive transmission probability p_t to FSA and ALOHA-Q, where t the frame number; $t = 1, 2, \cdots$. In the proposed protocol, an active node transmits its packet with probability p_t in the selected slot in Frame t. It implies that packet transmission is deferred to the next frame with probability $1 - p_t$. The transmission probability p_t is dynamically updated in a frame-by-frame manner, similarly to the update of the Q-table;

$$p_{t+1} = p_t + \beta(b_t - p_t) = (1-\beta)p_t + \beta b_t, \qquad (4)$$

with the initial condition $p_1 = 1.0$, where β is the learning rate for transmission probability; $0 \leq \beta \leq 1$, and $b_t$is the reward at Frame t, which is defined as

$$b_t = \begin{cases} B_{\mathrm{succ}}, & \text{for successful transmission,} \\ B_{\mathrm{fail}}, & \text{for unsuccessful transmission,} \\ B_{\mathrm{wait}}, & \text{for no transmission,} \end{cases} \qquad (5)$$

In order for (4) to be a valid transmission probability, it is necessary that $0 \leq B_{\mathrm{succ}}, B_{\mathrm{fail}}, B_{\mathrm{wait}} \leq 1$. Similarly to (2), from (4) the updated value p_{t+1} is an internally dividing point between p_t and b_t at ratio of β: $(1-\beta)$. Since $p_1 = 1.0$ and $0 \leq \beta \leq 1$, an inequality

$$\min[B_{\mathrm{succ}}, B_{\mathrm{fail}}, B_{\mathrm{wait}}] \le p_t \le \max[1.0, B_{\mathrm{succ}}, B_{\mathrm{fail}}, B_{\mathrm{wait}}] \qquad (6)$$

holds for any$t$. Note that from (4), transmission probability p_t at an active node which defers the packet transmission is also updated with reward B_{wait}. This operation is introduced to avoid long-term deferral of packet transmission, particularly for small transmission probability p_t. Meanwhile, Q-table is kept unchanged when packet transmission at an active node is deferred, as shown in (2) and (3). Notice here that the protocol $\beta = 0.0$ degenerates into its original one, FSA and ALOHA-Q without transmission probability, since $p_t = 1.0$ for any$t$.

[Example 2] A trace of transmission probabilityp_t in the case of a concise example in Figure 1 is given in Table 1 for $\beta = 0.5$. For example, unsuccessful packet transmission of Node 1 in Frame 2 decreases its transmission probability, from$p_2 = 1.0$ to $p_3 = (1-\beta)p_2 - \beta B_{\mathrm{fail}} = 0.55$. Then, successful packet transmission of Node 1 in Frame 3 increases $p_t$as $p_4 = (1-\beta)p_3 + \beta B_{\mathrm{succ}} = 0.775$.

Table 1. Transmission probability p_t in the case of Figure 1 for$\beta = 0.5$, $B_{\mathrm{succ}} = 1.0$ and $B_{\mathrm{fail}} = 0.1$

Frame t	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
Node 1	1.0	1.0	0.55	0.775	0.4375
Node 2	1.0	1.0	1.0	0.55	0.775
Node 3	1.0	1.0	0.55	0.325	0.2125

5. SIMULATION RESULTS

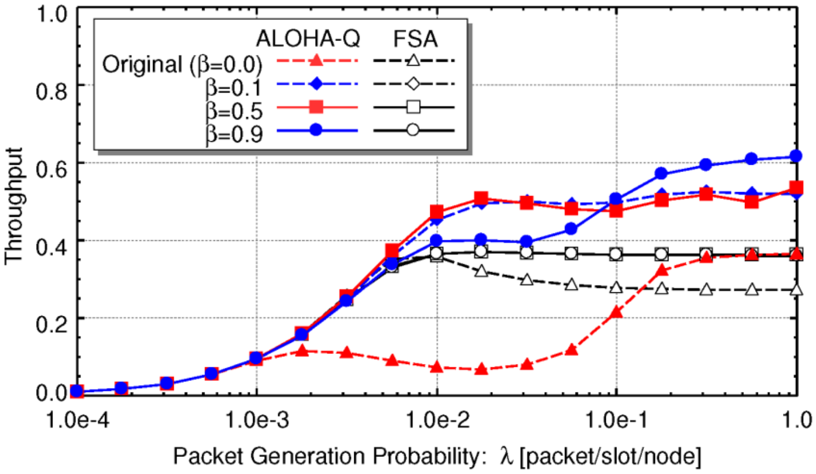
The effect of the transmission probability on the performance of FSA and ALOHA-Q is confirmed by means of exhaustive computer simulation. The simulation is programmed in C-language. The values of the parameters used are tabulated in Table 2.

Table 2. Simulation parameters

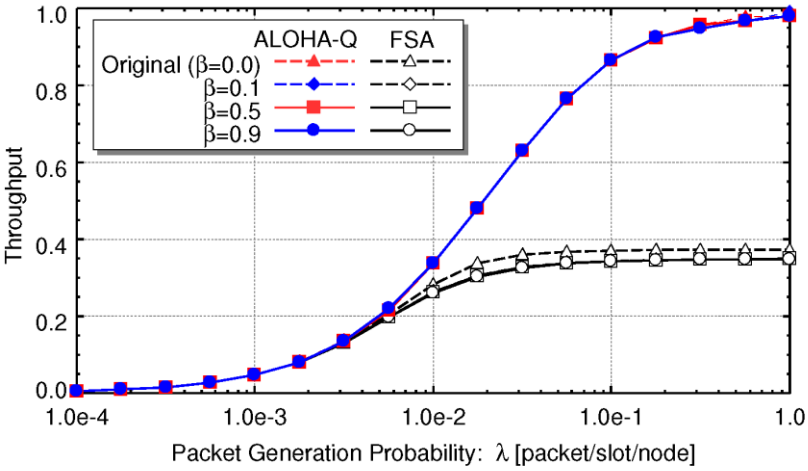
Parameter	**Value**
Number of nodes, N	$50, 100$
Frame length, L	50 [slot]
Number of simulated frames	10^6 [frame]
Reward, R_{succ}	1.0
Reward, R_{fail}	-1.0
Learning rate, α	0.1
Reward, B_{succ}	1.0
Reward, B_{fail}	0.1
Reward, B_{wait}	1.0
Learning rate, β	1.0

Here, it follows from (6) that $0.1 \le p_t \le 1.0$. We suppose a constant frame length of $L = 50$and two scenarios; the one is the case of excessive number of nodes $N = 100\ (= 2L)$, which may cause overloaded traffic condition, and the other is the case of$N = 50\ (= L)$.

Throughput and the average of packet transmission probability are shown in Figures 2 and 3, respectively.

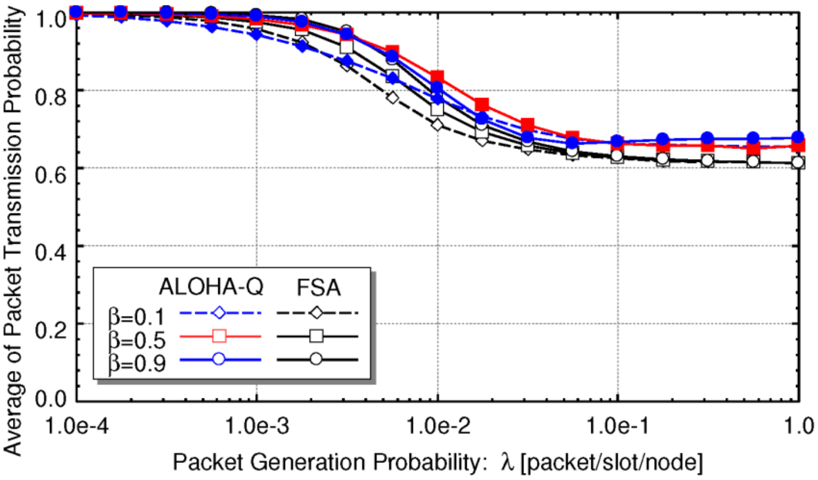


(a)$N = 100$ (overloaded traffic condition)

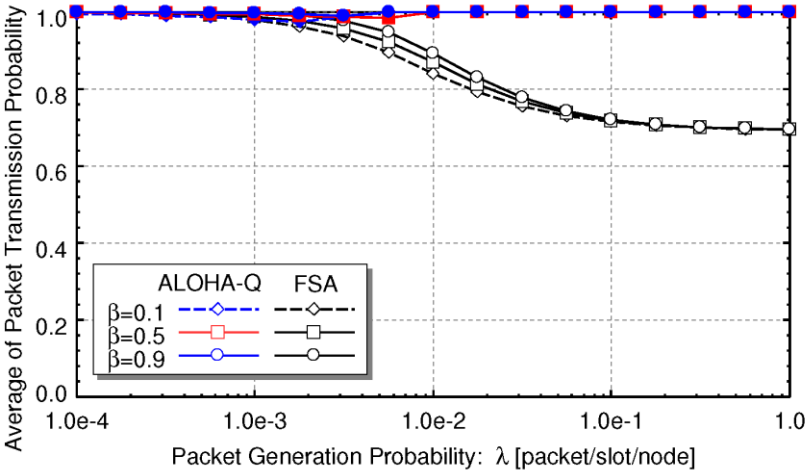


(b)$N = 50$ (moderate traffic condition)

Figure 2. Throughput for $L = 50$ and (a) $N = 100$ and (b) $N = 50$.



(a) $N = 100$ (overloaded traffic condition)

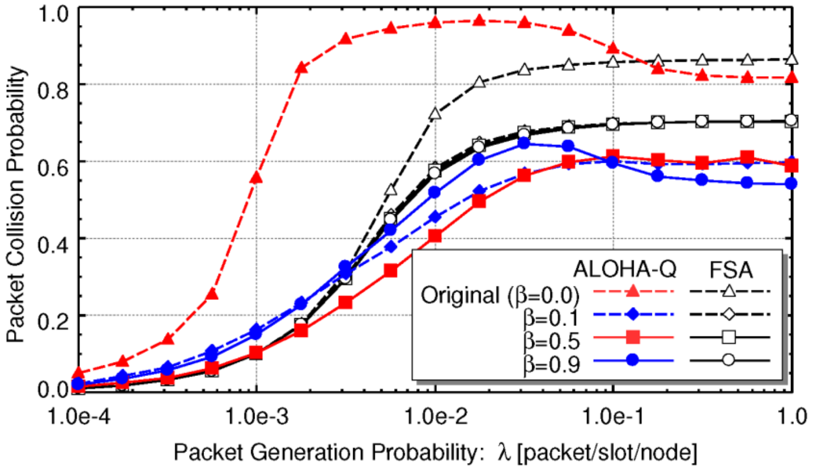


(b) $N = 50$ (moderate traffic condition)

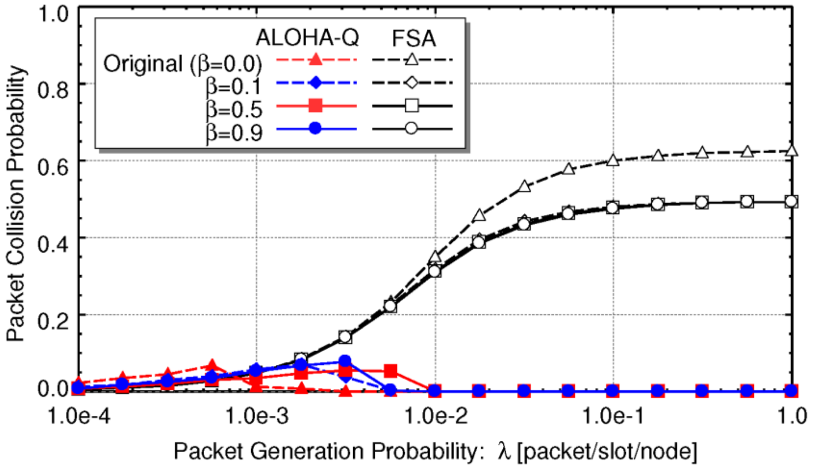
Figure 3. Average of transmission probability for $L = 50$ and (a) $N = 100$ and (b) $N = 50$.

From Figure 2(a) it is observed that for $N = 100$, the introduction of adaptive transmission probability p_t succeeds in improve throughput for both original cases of ALOHA-Q and FSA, which are equivalent to the case of $\beta = 0.0$. Meanwhile, from Figure 2(b) no effect of the adaptive transmission probability can be found on the throughput of ALOHA-Q for $N = 50$, which implies that Q-learning may accomplish ideal slot assignment to each node with or without transmission probability. By contrast, slight throughput degradation is caused in FSA for $N = 50$. Figures 3(a) and 3(b) show the average of the transmission probability p_t in ALOHA-Q and FSA for $N = 100$ and $N = 50$, respectively. It follows from Figure 3 that the transmission probability in average decreases except for the case of ALOHA-Q with adaptive transmission probability for$N = 50$, as the packet generation probabilityλincreases. Exceptionally, in ALOHA-Q with adaptive transmission probability for $N = 50$ the average of packet transmission probability is almost kept constant p_t for any λ. In the original ALOHA-Q and FSA, the transmission probability is constantly set to $p_t = 1.0$ for any t. As shown in Figures 2(a) and 3(a), the adaptation of transmission probability with Q-learning serves to improve the throughput for the overloaded traffic condition; $N = 100$.

Throughput of the original ALOHA-Q in Figure 2(a) is worse than that of the original FSA, particularly for around $10^{-3} < \lambda < 0.3$. This deterioration is caused by the rapid increase inthe probability of packet collision, as shown in Figure 4(a). In contrast, as shown in Figure 4(b), ALOHA-Q with transmission probability can realize low packet collision probability, which coincides with high throughput of ALOHA-Q with or without transmission probability shown in Figure 2(b).



(a) $N = 100$ (overloaded traffic condition)



(b) $N = 50$ (moderate traffic condition)

Figure 4. Packet collision probability for $L = 50$ and (a) $N = 100$ and (b) $N = 50$.

In the original ALOHA-Q, the update of the Q-table through Q-learning may narrow the selection range of possible slots in a frame for packet (re)transmission. If a sufficient number of slots, compared to the number of active nodes at the beginning of a frame, exist in a frame, packet collision due to such narrowing can be avoidable. However, packet collision is more likely to happen, if there exist an excessive number of active nodes, compared to the frame length. The possibility that two or more active nodes have an identical slot number whose $q_{t,\ell}$i is maximum in the Q-table increases. Consider the case of $\lambda = 10^{-2}$as an example. The distribution of the number of transmitted packets in slot is depicted in Figure 5.

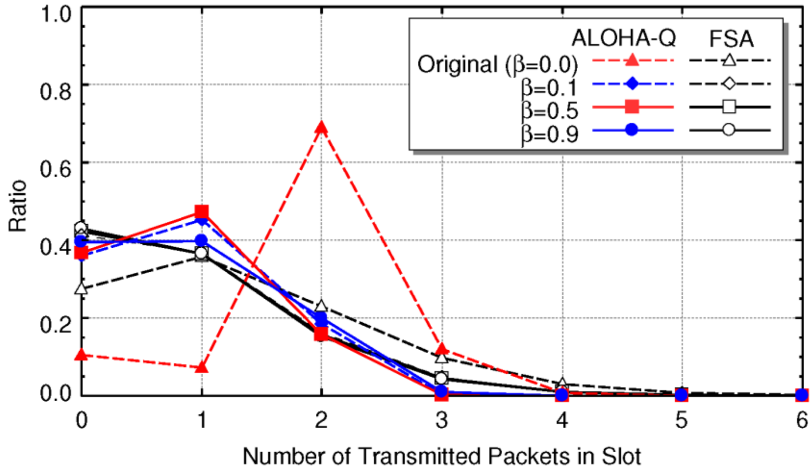


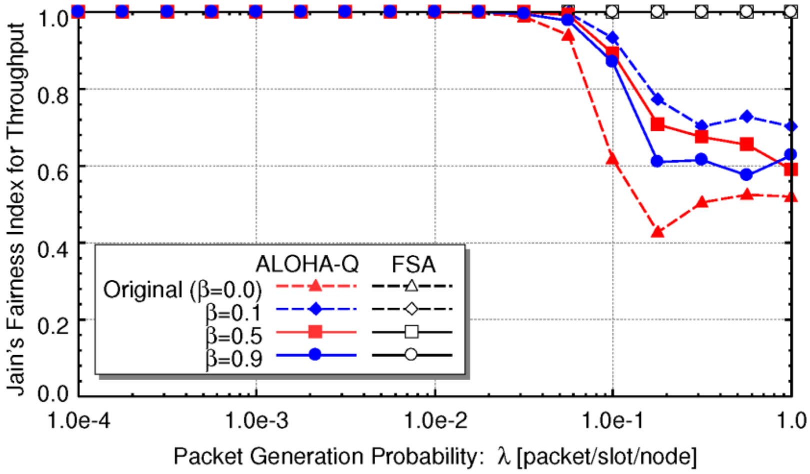
Figure 5. Distribution of the number of transmitted packets in slot for $L = 50$, $N = 100$ and $\lambda = 10^{-2}$.

From Figure 5, it can be observed that idle slots of ALOHA-Q with $\beta = 0.0$ are about 10%, successful slots, which is equivalent to throughput, is less than 10%, and packet collision with two packets happens with ratio of around 70%.

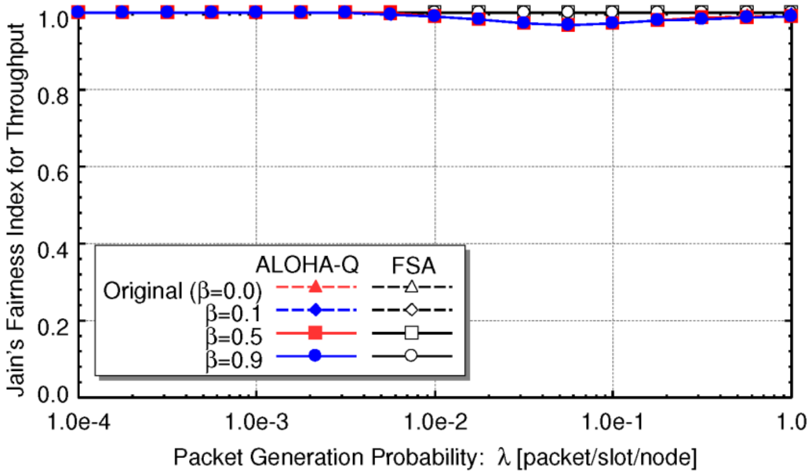
From the above observation, it appears that only a fraction of nodes succeeds in packet transmission and that the rest of nodes are likely to be included in packet collision or to defer packet transmission. In order to examine the fairness among nodes, in Figure 6 we show Jain's fairness index [13] with respect to throughput. Jain's fairness index is defined as

$$FI = \frac{\left(\sum_{n=1}^{N} S_n\right)^2}{N \sum_{n=1}^{N} S_n^2}, \qquad (7)$$

where S_n is throughput of node n.



(a) $N = 100$ (overloaded traffic condition)



(b) $N = 50$ (moderate traffic condition)

Figure 6. Fairness index with respect to throughput for $L = 50$ and (a) $N = 100$ and (b) $N = 50$.
From Figure 6(a) the fairness index of FSA with or without transmission probability is kept 1.0. However, the fairness index of ALOHA-Q falls down, which degradation can be mitigated to some extent by introducing transmission probability. In contrast, from Figure 6(b), Jain's fairness index of nearly 1.0 can be maintained in the range of large packet generation probability for $N = 50$.

In consequence, from Figures 2-6 incorporation of adaptive transmission probability improves the performance of ALOHA-Q and FSA for the case of overloaded traffic condition and exhibits comparable performance to the original ALOHA-Q for the case of moderate traffic condition.

6. CONCLUSION

In this paper, the incorporation of adaptive transmission probability to ALOHA-Q was proposed in order to mitigate overloaded traffic conditions. The Performance of the proposed protocol was examined by means of exhaustive computer simulation. Numerical results reveal that the proposed protocol can mitigate performance degradation of ALOHA-Q under overloaded traffic conditions and that the proposed protocol exhibits comparable performance to ALOHA-Q for moderate traffic conditions.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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