Effect of Exponential Backoff on the Performance of Network Coding in a Slotted Aloha Network

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***Abstract*— In this paper we study the effect of exponential backoff on the performance of network coding in a simple ad hoc network working based on slotted Aloha. To this end, we devise an analytical model based on an open multi-class queueing network to represent our scenario. In this model, by mapping backoff status of packet transmissions onto suitable classes of customers on one hand, and employing two previously introduced modeling principles to represent packet combination and packet multicasting, needed in network coding scenarios, on the other hand, we are able to find the maximum stable throughput, i.e., the maximum packet arrival rate at which the queueing nodes remain stable. We observe that exponential backoff may reduce the amount of superiority of network coding to simple routing. Finally, we confirm our analytical model by some simulations.**

Keywords*— *Network coding, slotted Aloha, exponential backoff, queueing network.

I. Introduction

For modern wireless communication networks, different types of random access protocols have been proposed. One of the effective factors in enhancing the performance of random access MAC protocols is their ability in adjusting with dynamic environment. Exponential backoff mechanism is an efficient way in this respect. Today, exponential backoff is a non-separable element of IEEE 802.11-based family of MAC protocols.

Up to now, many research works have been tailored to enhance the throughput of wireless networks. In this respect, new MAC and routing schemes have been proposed. Network coding (NC) plays an important role in this respect. In many research works (e.g., [1]-[5]) the joint effect of network coding and scheduling has been considered. Also, in some works (e.g., [5]-[7]) the joint effect of random access MAC protocols and network coding has been investigated. In [5],[8] the effect of network coding in a slotted Aloha-based tandem network, for multi-cast scenarios, has been considered. In [6], the superiority of network coding in a simple WLAN, for unicast scenarios has been studied. In [7], a simple slotted Aloha network working based on NC has been modeled. In [9], two different schemes of network coding in a simple WLAN, i.e., digital and analog, have been compared. In most works on the combination of network coding and random access MAC protocols, it has been shown that NC enhances the throughput.

In order to enhance the performance of random access MAC protocols, usually exponential backoff mechanism is employed. Now, an important question arises that whether NC is able to outperform the random access protocol with exponential backoff too. In other words, since exponential backoff may lead the random access protocol to a more efficient one by reducing the collisions, we are interested in knowing how exponential backoff affects on the performance of NC in a random access MAC protocol. Up to now, some research works have focused on the combination of NC and the well-known random access MAC protocol, i.e., IEEE 802.11. In [11], the authors propose a practical protocol (COPE) and show the superiority of NC. In [12], NC enhances the retransmission schemes regarding QoS of different packets, by cooperating with EDCA mechanism in IEEE 802.11e. Although in these works exponential backoff exist in the MAC protocol distinct effect of NC in the cases of with/without backoff is not known. In [13], it is shown that optimum algorithm proposed for random access MAC is not necessarily optimal when exponential backoff is included. This is due to the fact that exponential backoff adds memory to the channel, so dealing with the problem becomes difficult. This is more serious when we consider non-saturation status for the nodes, i.e., nodes are not backlogged forever. It is worth noting that in most analytical works on considering NC and 802.11 MAC protocol, saturated nodes have been assumed.

In this paper we focus on analytical modeling of a simple ad hoc network comprised of a few terminal nodes and a relay node. Terminal nodes send packets destined to the others based on slotted Aloha protocol in a single hop or two hop manners. In the latter case, the relay node intervenes the transmission. Our analytical model is an extension to the previously proposed model in [6],[9] in such a way to be able to include the effect of different backoff stages of the nodes. To this end, we exploit a multi-class open queueing network ([14]) and map backoff stages on different classes of the packets. By writing traffic equations of the queueing network and applying the stability condition, we are able to find the maximum stable throughput, i.e., the maximum arrival rates such that the network remains stable. We will observe that exponential backoff reduces the superiority of NC to traditional routing compared to the case of without exponential backoff. We also do some simulations to show the validity of our model.

The remaining of this paper is as follows. In Section II, we describe our scenario and related assumptions. In Section III, we first introduce our analytical model and extract important parameters such as transmission and collision probabilities, utilization factor, and maximum stable throughput. In Section IV, we present some numerical and simulation results. Section V concludes the paper.

II. Network Scenario and the Proposed NC-Based Relaying Scheme

In this section, we describe our network scenario and clarify the proposed relaying scheme. We consider a simple ad hoc network with seven nodes as shown in Fig 1. Nodes 1, 2, 3, 4, 5, 6 are terminal nodes and are located around node 7 which is the relaying node (RN) and plays the role of relaying. We have assumed that each terminal node has two neighbors, one at each side. For example, nodes 3 and 5 are considered to be neighbors of node 4. Fixed size packets are produced with the rate λ at each terminal node and are destined to other terminal nodes equally likely. The transmission range is equal to $\sqrt{3}R$ (see Fig. 1). So each terminal node can transmit packets to its neighbors directly in a single hop manner; however, for conveying the packets to non-neighboring nodes, the packet should be first transmitted to RN and then be relayed to its destination. The time is divided into fixed and equal intervals called time slots. Each node that has packets to transmit waits for a random number of time slots. We model this random waiting time with the probability of transmission. If a node receives its appropriate packet successfully, it sends back an acknowledgement message (ACK message) to the transmitter node. A packet transmission is successful provided that in the interference range of the receiver no simultaneous transmission occurs. For the sake of simplicity, we consider the interference range to be equal $2R$, more than transmission range. Thus collisions may occur due to simultaneous transmissions. In this case, the collided packets should be retransmitted toward their destinations, but after each collision transmission probabilities of the corresponding nodes are halved in order to decrease the chance of another collision (i.e., exponential backoff). Such a halving process continues until the packet is transmitted successfully. In this case, the transmission probability of the transmitter node resets to its initial value.

Similar to [6],[10] in our scenario packet relaying is based on NC. We have considered several buffers at RN for storing received packets destined to each terminal node, distinctly, so they can be combined by suitable packet partners. The packet partners are chosen based on a simple principle that each node can overhear packets transmitted by its neighbors. So it should keep its own packets and its overheard ones for a while.

Some examples of suitable packet partners according to node arrangement in Fig.1 can be (1⟶4, 4⟶1), (3⟶1, 6⟶4), (2⟶5, 5⟶2), etc. The notation $a \rightarrow b$ denotes a packet with its source at *a*, and its destination at *b*. For instance, consider the second packet partners mentioned above. In this case, packet from node 3 destined to node 1 is combined with another packet from node 6 destined to node 4 in RN. Then, RN broadcasts the combined packet. Node 4 is the neighbor of node 3, so it overhears the packet transmitted to RN from node 3. Besides, it receives the combined packet from RN. Therefore, node 4 is able to decode its desired packet whose source is node 6. A similar process occurs for node 1, so this node can receive its packets too. In this paper, we consider packet partners in the form of $(a \rightarrow b, b \rightarrow a)$ in order to simplify subsequent analysis. In this case, both nodes a and b know their own transmitted packets. By receiving the combined packet from RN successfully, they will be able to recognize their desired packets. In our scenario, we assume a vector, $\vec{b} = (b_1, b_2, b_3, b_4, b_5, b_6, b_7)$, that indicates the backoff stage of the packet at each node. Backoff stage is the number of collisions that have occurred up to now while transmitting a typical packet. When the number of consecutive collisions for

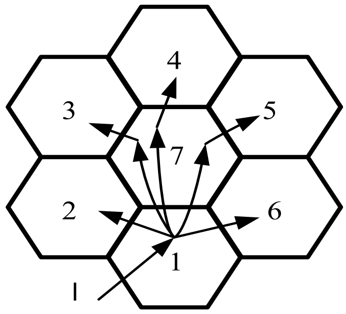

Fig.1. A simple ad hoc network. Only packets arrived at node 1 and destined to other nodes have been shown.

a typical packet reaches b_{max} then the corresponding transmission probability remains constant until the packet is received successfully by its desired receiver. After each collision the backoff stage for the transmitted packet is increased by one. When a packet is received successfully by its desired destination, the backoff stage of the packet becomes zero. As indicated before, changing the backoff stage will change the transmission probability of each packet. In the case of saturation the transmission probability of each packet is P_0 before any collision occurs for this packet, i.e., $p_{tr,i0} = P_0$; $1 \leq i \leq 7$. After the first collision the transmission probability of the packet is halved, i.e., $P_0/2$, and the same process repeats after next consecutive collisions, i.e., $p_{tr,ij} = P_0/2^j$ $1 \leq i \leq 7$ where i and j denote the transmitter node and backoff stage, respectively. Collision occurs in the following situations:

1. If in a time slot, more than one node, e.g., u, v attempt to send packets to non-neighboring nodes, the transmitted packets will collide because RN cannot receive two or more packets simultaneously. In this case, both b_u and b_v will increment by one.
2. If two nodes try to send packets to a common destination, both transmissions will be failed. For instance, consider the situation in which nodes 4, 6 send packets to node 5 in a time slot. i.e, (4⟶5) and (6⟶5). In this case, both b_4 and b_6 will increment by one.
3. If a node is not only a transmitter but also a receiver at the same time, only the packet which originates from that node can be received successfully. For example, assume two transmissions, (1⟶2) and (2⟶5). In this example the packet that went out from node 1 cannot be received at node 2 definitely because of the half-duplex mode in all nodes. Therefore, the packet should be retransmitted from node 1 and its stage of backoff will increment.

It is worth mentioning that, according to our assumption, the backoff stage of node 7 (RN) will increase when the transmitted packet fails to reach at least one of its destinations. This procedure preserves until the failed packet(s) is eventually attained by its destination(s) and then the RN attempts to send new packets with zero backoff stage. It is important to note that in the corresponding conventional routing as the simple relaying scenario, transmission to neighboring nodes is similar to the proposed NC, however for transmitting to non-neighboring nodes the packet is simply relayed by RN without any combination.

III. Analytical Modeling and Computation of Maximum Stable Throughput

In this section we propose an analytical model in order to analyze the combined NC and exponential backoff. In our modeling approach we map each wireless node onto a queueing node and packets onto costumers. Then we have an open queueing network (QN) comprised of seven single server nodes [14]. When packets are received successfully by their final destinations the corresponding customers exit from the queueing network. In this QN, customers arrive at terminal nodes and after routing among some queueing nodes (based on relaying scheme) they reach their final destinations. In order to distinguish between transmitted packets due to different backoff stages we exploit multiclass customers in our model. The class shows both the destination of the packet and its backoff stage. For example if the class of a specific packet is 6_3 it means that the packet is destined to node 6 and its backoff stage is 3, i.e., its transmission has experienced three collisions up to now. The classes are used as indices for different routing probabilities among the queueing nodes.

For non-saturation case the effective transmission probability equals $\rho_{ij} p_{tr,ij}$ where ρ_{ij} is the traffic intensity of node *i* corresponding to class *j*. It denotes the steady state probability that node *i* (a single server queueing node) has a packet of class *j*. In the case of network coding scenario, two important phenomena take place, packet combination and packet multicasting. According to our relaying scenario only two packets may be combined at RN and then multicast to two other nodes. In order to reflect these two important phenomena in our queueing network we exploit two modeling principles [6],[9]. First, to model the multicasting event we scale the service time and send the packet toward its destinations with probability 1/2. Thus we need two packets to be transmitted instead of one packet to be multicast, so we need one extra packet (see Fig.2). Second, the combination of two packets must be modeled too. So we use the concept of packet classes to reflect this phenomenon. In this respect, we consider a new customer class for two packets originated from different nodes and combined at RN in order to be multicast to their favorable destinations (see Fig.2). We must consider different classes for various possible combinations. We have 6 terminal nodes, so we will have $\binom{6}{2}$ different possible new packet classes, however regarding the relaying scheme in Section II, all these classes are not required.

A. Routing probabilities

Now we discuss how to compute different probabilities with which different customers (with different classes) may be routed among queueing nodes. We know that all packet combinations happen at RN, so we map packet combinations as new customer classes at the input of RN according to modeling principles indicated before. Let $r_{ik_j.7m_0}$ denote the routing probability that a packet of class *k* with backoff stage *j* departed from node *i*, is routed to RN (node 7) as class *m* with backoff stage 0. In fact, when a packet is successfully routed to RN, it is a new packet at that node that has not experienced any

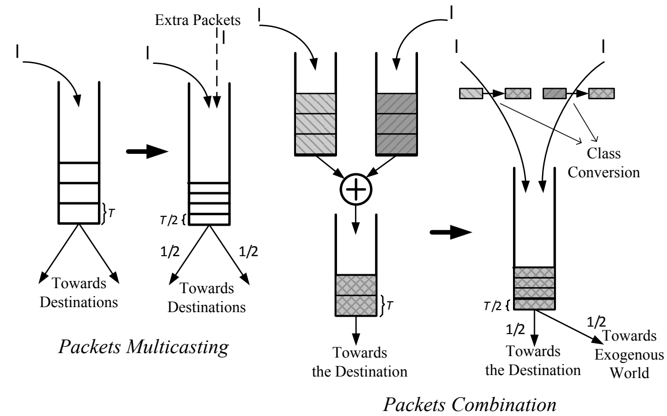

Fig.2. Illustration of two modeling principles; packet multicasting and packet combination [6],[9].

collision. Thus, it will be transmitted with backoff stage zero. The class also shows the packet's destination at each node. We have the following relations in general:

$$r_{ik_l,7m_0} = \prod_{\substack{j\neq i\\ j=1:7}} \left(1 - \sum_{v=0}^{b_{max}} \rho_{j_v} p_{tr,jv}\right);\quad |i-k| \neq 0,1,5,\ m = ik. \tag{1}$$

Eq. (1) denotes the routing probability of a packet with backoff stage *l* from node *i* destined to node *k* through RN. As we indicated before, a transmitted packet is received successfully provided that no other simultaneous transmissions in the neighborhood of the receiver exist. Since RN is within the neighbors of all nodes, in (1) we should not have any other transmission. Moreover,

$$r_{7m_l,7y_0} = \left(1 - \prod_{j\in\{y\}\cup(R_y - R_x)} \left(1 - \sum_{v=0}^{b_{max}} \rho_{j_v} p_{tr,jv}\right)\right) \prod_{j\in\{x\}\cup R_x} \left(1 - \sum_{v=0}^{b_{max}} \rho_{j_v} p_{tr,jv}\right);\ m = xy. \tag{2}$$

In (2) we have considered the probability that a combined packet has been transmitted from RN and only one of the destinations receives successfully, so the packet is routed again to RN as a class-*y* packet and it should be retransmitted to another destination (node *y*). It is worth mentioning that R_x denotes the set of $x's$ neighboring nodes. Also,

$$r_{7m_l,0} = \prod_{j\in R_x\cup R_y} \left(1 - \sum_{v=0}^{b_{max}} \rho_{j_v} p_{tr,jv}\right);\ m = xy, \tag{3}$$

$$r_{7k_l,0} = \prod_{j\in\{k\} U R_k} \left(1 - \sum_{v=0}^{b_{max}} \rho_{j_v} p_{tr,jv}\right), \tag{4}$$

$$r_{ik_l,0} = \prod_{j\in\{7,k\} U R_k} \left(1 - \sum_{v=0}^{b_{max}} \rho_{j_v} p_{tr,jv}\right);\quad i,k = 1,2,\dots,6,\ |k-i| = 1,5\ . \tag{5}$$

where in (3)-(5) the routing probabilities to exogenous world (node 0), equivalent to successful packet routing to the destinations have been considered.

B. Traffic equations and the maximum stable throughput

Traffic equations show how we can find the packet arrival rate at each node. In a stable network the departure rate equals the arrival rate when we do not have any blocking. In the following equations α_{ik_j} denotes the class-*k* packet arrival rate at node *i* (the packets will be transmitted with backoff stage *j*), and λ_{ik_j} is the packet generation rate at node *i* destined to node *k* with backoff stage *j*. Obviously generated packets are new packets, so they are transmitted with backoff stage 0. So we have:

$$\alpha_{ik_0} = \lambda_{ik_0},$$
$$\alpha_{ik_j} = \alpha_{ik_{(j-1)}}\left(1 - r_{ik_{(j-1)},0}\right);\ j \neq 0, b_{max},$$
$$\alpha_{ik_j} = \alpha_{ik_{(j-1)}}\left(1 - r_{ik_{(j-1)},0}\right) + \alpha_{ik_j}\left(1 - r_{ik_j,0}\right);\ j = b_{max},$$
$$1 \le i \le 6,\ 1 \le k \le 6,\ |i-k| = 1,5. \quad (6)$$

In (6) the packet arrival rates at terminal nodes destined to their neighbors have been considered. However, the packet arrival rate at terminal nodes destined to non-neighboring nodes are computed as

$$\alpha_{ik_0} = \lambda_{ik_0},$$
$$\alpha_{ik_j} = \alpha_{ik_{(j-1)}}\left(1 - r_{ik_{(j-1)},7m_0}\right);\ j \neq 0, b_{max},$$
$$\alpha_{ik_j} = \alpha_{ik_{(j-1)}}\left(1 - r_{ik_{(j-1)},7m_0}\right) + \alpha_{ik_j}\left(1 - r_{ik_j,7m_0}\right);\ j = b_{max},$$
$$1 \le i,k \le 6,\ |i-k| \neq 1,5,0,\ m = ik. \quad (7)$$

where *m* represent the class of the transmitting packet which was explained before. Obviously, in the case of simple routing, packet combination does not exist and *m* equals *k*.

We have the following equation for the packet arrival rate at RN:

$$\alpha_{7m_0} = \sum_{n=0}^{b_{max}} \alpha_{xy_n} r_{xy_n,7m_0} + \sum_{n=0}^{b_{max}} \alpha_{yx_n} r_{yx_n,7m_0},$$
$$\alpha_{7m_j} = \alpha_{7m_{(j-1)}} r_{7m_{(j-1)},7m};\ j \neq 0, b_{max}$$
$$\alpha_{7m_j} = \alpha_{7m_{(j-1)}} r_{7m_{(j-1)},7m} + \alpha_{7m_j} r_{7m_j,7m};\ j = b_{max},$$
$$m = xy,\ 1 \le x,y \le 6,\ |x-y| \neq 1,5,0. \quad (8)$$

$$\alpha_{7k_0} = \frac{1}{2}\alpha_{7m_0} r_{7m_l,7k_0},$$
$$\alpha_{7k_j} = \alpha_{7k_{(j-1)}}\left(1 - r_{7k_{(j-1)},0}\right);\ j \neq 0, b_{max},$$
$$\alpha_{7k_j} = \alpha_{7k_{(j-1)}}\left(1 - r_{7k_{(j-1)},0}\right) + \alpha_{7k_j}\left(1 - r_{7k_j,0}\right);\ j = b_{max},$$
$$m = xy,\ 1 \le x,y \le 6,\ |x-y| \neq 0,1,5,\ k = x,y. \quad (9)$$

where the packet arrival rate in (8) denotes the arrival rate at RN regarding the modeling principle of packet combination. In (9) the first equation indicates that the combined packet is received by one of destinations successfully and by another one unsuccessfully. The second and third equations indicate that the packet departure from RN has not been received by the desired destination (due to collision) and fed back to RN. Clearly it should be transmitted with the next backoff stage. It is important to mention that the traffic equations for the case of simple routing can be derived from some mathematic simplifications on the aforementioned equations. Due to lack of space we ignore writing equations in this case. Traffic intensities in (1)-(5) and service rates are computed as in the following:

$$\rho_i = \sum_{\substack{k=1 \\ k \neq i}}^{7} \sum_{v=0}^{b_{max}} \rho_{ik_v},\quad \rho_{ik_v} = \frac{\alpha_{ik_v}}{\mu_{i_v}},\ \mu_{i_v} = p_{tr,iv};$$
$$1 \le i,k \le 6,\ |i-k| \neq 0,\ 0 \le v \le b_{max}, \quad (10)$$

$$\rho_7 = \sum_{k=1}^{6} \sum_{v=0}^{b_{max}} \rho_{7k_v} + \sum_m \sum_{v=0}^{b_{max}} \rho_{7m_v};$$
$$\rho_{7m_v} = \frac{\alpha_{7m_v}}{2\mu_{7_v}},\ \rho_{7k_v} = \frac{\alpha_{7k_v}}{\mu_{7_v}},\ \mu_{7_v} = p_{tr,7v};$$
$$m = ik,\ 1 \le i,k \le 6,\ |i-k| \neq 1,5,0. \quad (11)$$

where μ_{i_v} denotes the service rate of terminal node i with backoff stage v, and μ_{7_v} shows the service rate of RN at backoff stage v. The coefficient 2 in (11) refers to the modeling principle discussed in Section III (see Fig. 2). Apparently (1)-(11) must be solved recursively. Then we are able to find traffic intensities. According to the stability criterion all traffic intensities must be smaller than one. By increasing λ one of the traffic intensities becomes 1 which means that one of the terminal nodes or RN reaches the instability threshold. In other words, for rates beyond this rate the system becomes unstable, so it is the maximum stable throughput of the network. Hence,:

$$\lambda_{max} = min\ \lambda|_{(\rho_i<1,\rho_N=1) or (\rho_N<1,\rho_i=1,\rho_j<1)\ for\ i,j=1,2,\ldots,6, j\neq i}. \quad (12)$$

IV. NUMERICAL RESULTS

In this section, we compare the normalized throughput for the combination of NC and exponential backoff with the case of without NC. The network throughput is affected by two opposite effects. By decreasing the transmission probabilities we reduce the service rate which leads to a reduction in network throughput, but it reduces the chance of collision occurrence and in this way it will improve the network throughput. So we will have an optimum transmission probability. Exponential backoff plays an important role in improving the network throughput by controlling the transmission probabilities, dynamically. When the transmission probabilities are high we will have great chance of collision which decreases the network throughput. Exponential backoff solve this problem by decreasing the transmission probabilities of the collided packets. Thus the chance of collision will decrease and the network throughput enhances. However, if this procedure continues again the throughput will fall due to low transmission probability, so when the packets are received by their desired destinations the transmission probabilities are being set to their initial values.

On the other hand, by exploiting NC the number of packet transmissions decreases and then collisions occur less often. Thus when collision probability is high the superiority of NC is more significant. Therefore, since exponential backoff promotes the performance of slotted Aloha by reducing collisions, it appears that superiority of NC to simple routing reduces. From Figs. 3,4 it can be observed that the proposed combination of NC and exponential backoff outperforms the combination of simple routing and exponential backoff more than 6% (in their optimal transmission probabilities) for b_{max}=1, while for b_{max}=0 the outperformance is about 23%. However, we can observe that exponential backoff leads to more enhancements in the case of NC compared with simple routing (compare the results of b_{max}=1 and b_{max}=0, in Figs. 3,4, distinctly). Figs. 3,4 also show that unsuitable b_{max} may degrade the performance (see the results of b_{max}=2).

In order to validate our analytical approach we carry out some simulations in MATLAB environment. We have considered Poisson arrival process at all terminal nodes. We have considered a large time interval and computed the ratio of the number of successfully received packets at their destinations to the number of the newly generated packets at the same time interval. In stable condition the ratio equals one, but by increasing the packet generation rate (λ), the ratio deviates from unity indicating that the system becomes unstable. The rate at which the knee of the curve occurs shows the maximum stable throughput that is in good match with the analytical results (see Fig. 5 and compare it with corresponding results in Figs. 3,4).

V. Conclusion

Regarding the importance of both network coding and exponential backoff, we considered a simple ad hoc network comprised of six terminal nodes and an RN which has the relaying role in the network. We proposed a combined NC and exponential backoff packet routing scheme. Thus by applying NC we decreased the number of transmissions and by using exponential backoff we controlled the transmission probabilities in order to increase the network throughput. In order to evaluate the proposed combined scheme we used a queueing network model. By mapping the details of our routing scheme as well as backoff status to the suitable parameters of the queueing network, solving the traffic equations, and applying the stability criteria, we found the maximum stable throughput. Also, we validated our analytical approach by simulation. We observed that exponential backoff may degrade the NC superiority to simple routing, however, it is more effective in the case of NC.

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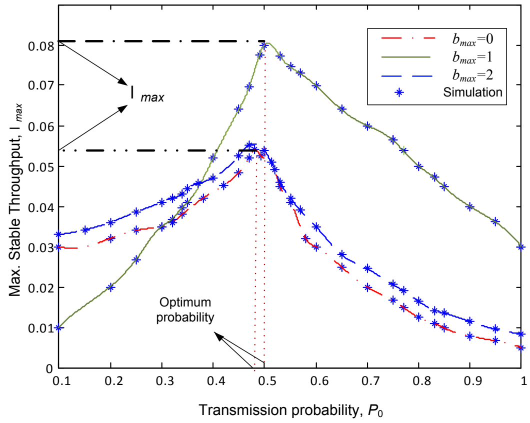

Fig.3. Illustration of maximum stable throughput versus transmission probability in the case of simple routing for different backoff stages.

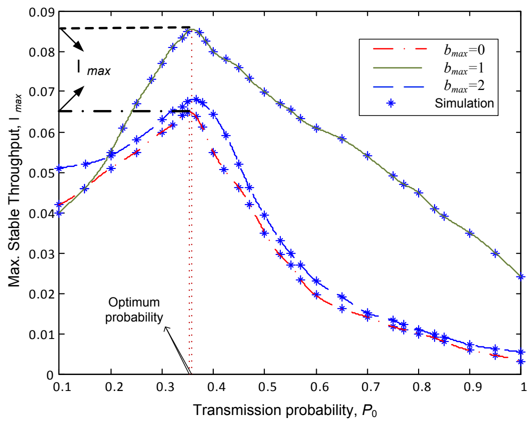

Fig.4. Illustration of maximum stable throughput versus transmission probability in the case of NC for different backoff stages.

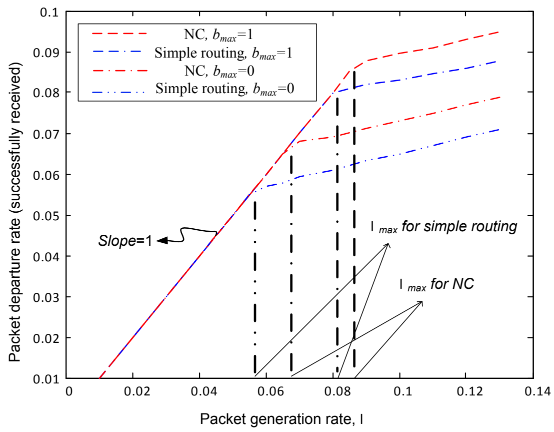

Fig.5. Rate of successfully received packets to the rate of generated packets for b_{max}=0,1 at corresponding optimal transmission probabilities.