Interference-aware relay assignment scheme for multi-hop wireless networks

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Abstract This paper proposes an interference-limited relay assignment scheme for multi-hop wireless networks that exploits cooperative diversity to cope with problems of wireless channels and to enhance data transmission reliability. By combining the selection and incremental relaying schemes and by taking into account the channel status information and queue length at each node, the cooperative scheme improves the packet dropped ratio and end-to-end delay due to retransmissions. The proposed method is based on local channel measurement and requires no topology information. In addition, this paper also investigates the interference problem produced by the relay nodes and the failure probability of the best relay selection. Extensive simulations conducted to evaluate the performance of the proposed scheme indicate that it effectively enhances the network performance in terms of the packet delivery ratio, energy consumption, and overall packet delay.

Keywords Cooperative communications · Interference-aware · Relay assignment · Channel state information · Queue size

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1 Introduction

Wireless channels suffer from many kinds of phenomena such as path loss, multi-path propagation, thermal noise, and time-variation. Generally, wireless channels can be considered as location-dependent, time-variation, random, and having a significant error rate [8]. Packet transmission may be corrupted by channel conditions, leading to poor reception and requiring retransmissions that significantly increase the end-to-end packet delay and reduce the overall network throughput. *Spatial diversity* can be a promising solution to compensate for these influences of the wireless channel, without increasing the transmission power or bandwidth-required for devices. Multiple-input multiple-output (MIMO) techniques are conventional forms of spatial diversity with physical antenna arrays at both the transmitter and the receiver to improve communication performance [15]. However, the approaches based on MIMO techniques require at each end device of higher cost and processing complexity. In contrast to a single user with multiple antennas, *cooperative diversity* is a potential solution to enhance the reliability and real-time performance of wireless networks in terms of the packet delivery ratio (PDR) and the end-to-end delay by increasing the probability of success for packet transmission, i.e., by reducing the packet error rate and retransmission times [24]. Many aspects of cooperative communication have been studied in recent years, including theoretical analysis for one-hop transmission [5, 15, 23], networking [1, 3, 18], and power control protocols [25, 26]. Depending on the ability of the relay to decode the received signal from the source, we find that two classical relay schemes are used, namely, *amplify-and-forward* (AF) and *decode-and-forward* (DF). In the AF scheme, the relay receives and amplifies the incoming signals from the source, including noise. Otherwise, in the DF

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scheme, the relay decodes, re-encodes, and transfers the messages from the source. At the destination, a suitable diversity-combining technique is used to recover the original messages from the source and relay.

On the basis of the relay techniques, Laneman et al. [15] categorized two adaptive strategies for a group of one source, one relay, and one destination, called selection relaying (SR) (or opportunistic relaying) and incremental relaying (IR). For SR scheme using either AF or DF, if the measured channel SNR is lower than a certain threshold, the source will retransmit the packet to the destination. Otherwise, the relay forwards the received message toward the destination, instead [4]. However, once the destination can decode the packet from the source successfully, the transmission from the relay and the packet-combining process at the destination are not necessary. Therefore, the utilization of network resources becomes inefficient. On the other hand, IR scheme exploits limited feedback from the destination to improve the efficiency in using the degrees of freedom of the channel. The source sends its packet to the relay and the destination. If the destination replies with a negative acknowledgment (NACK), the relay will retransmit the packet to the destination without considering the channel condition of the source–relay link. The received packet from the source–relay link thus may be decoded incorrectly, which causes more errors at the destination.

In this paper, we propose an adaptive strategy to overcome the drawbacks of the aforementioned two schemes and harness the advantages of cooperative diversity to improve network reliability and utilization efficiency. The proposed scheme is suitable for delay-tolerant and high-traffic applications such as multi-hop multimedia wireless networks using the DF scheme for flexible implementation in the existing hardware. The study combines the SR and IR schemes by taking into account the instantaneous channel state information (CSI) in distributed multi-hop wireless networks, where a group of neighboring nodes at each hop joins in the competition to become the best relay for the packet from the source. In addition, we employ TADR [20] as a background routing scheme; it is a proactive source routing scheme in which nodes periodically exchange network status information to find a suitable source–destination pair at each hop. While most previous studies investigate the evaluation of the bit error rate and the outage probability of the cooperative diversity models, this paper focuses on the system-level performance evaluation to enhance the network performance with the following contributions: (1) the proposed cooperative scheme with a group of a source, a destination, and a set of relays at each hop improves network performance in terms of the PDR, energy consumption, and overall packet delay; (2) the relay assignment process is based on the CSI and the current queue length at the transmitting buffer of each relay so that the most available path for information relaying is chosen; (3) probabilistic analysis regarding the failure of the best relay selection is provided; and (4) the influence of the interference caused by the relay assignment is considered.

The rest of this paper is organized as follows. In Sect. 2, we summarize the studies related to our study. In Sect. 3, we describe a system model for the cooperative model used in this paper. In Sect. 4, we discuss the cooperative transmission and relay assignment phases. In Sect. 5, we analyze the failure probability of the relay assignment scheme. In Sect. 6, we investigate the effect of relay interference. In Sect. 7, we present the performance evaluation. Finally, in Sect. 8, we conclude the paper.

2 Related studies

In this section, we review some related studies on cooperative networking and relay assignment schemes.

For single-hop networks, Bletsas et al. [4] proposed a simple relay selection policy to choose the best relay from a set of available neighbors. However, their work only considers single-hop transmission from the standpoint of probabilistic analysis with a fixed source–destination pair without considering the queue size. In [6], El-Sherif and Liu presented a novel cooperative scheme for random access networks that uses Markov chains and queuing analysis. This study investigated the protocol design and performance analysis for single-hop networks, where all nodes and the AP can communicate directly. However, cooperation is implemented through a predefined relay node, without using a relay assignment process.

For multi-hop networks, the authors in [9] incorporated the MAC layer and routing design to enhance the robustness of the routing protocol with the broadcast nature of wireless links. However, sleep/wake scheduling is needed for the guard nodes. Besides, Ibrahim et al. [11] also investigated an energy-efficient cooperative routing algorithm and devised a minimum-power scheme called minimum power cooperative routing. However, this scheme was mainly developed to discover the optimal cooperative routes for the distributed shortest path algorithms. In addition, Sharma et al. [21] solved the optimization problem of rate gains for multi-hop networks through joint routing and relay node assignment. In contrast, our study investigates relay assignment scheme and the end-to-end performance of network traffic.

Some schemes have proposed solutions to the relay assignment problem in cooperative networks. In [22], Uhlemann and Willig combined the relay assignment scheme and packet combining by the destination for wireless networks. However, their model belongs to the class of source-controlled schemes; i.e., the relay assignment is decided by the source, whereas our study investigates relay-controlled schemes. Moreover, medium access control (MAC) in [22] is followed by n-slot for acknowledgment from the destination and the relay nodes, which is fundamentally different from our approach. Alonso-Zarate et al. [2] presented a MAC protocol called PRCSMA to coordinate the retransmissions of the relays based on ARQ. However, this scheme does not take the channel condition and interference caused by the relay assignment process into account. In [13], a max—link relay selection scheme was incorporated the instantaneous strength of wireless channel and the status of the finite relay buffers to provide diversity gains for applications without latency constraints. However, the selection scheme in [13] simply considered the relay buffers to decide the available links that participate in the relay selection decision, i.e., a relay node with a full or empty data buffer cannot receive or transmit data respectively.

It is necessary to consider the impact of interference due to degradation in network performance on the design and deployment of wireless networks. The subject of [27] is related to either interference management and the probability of correct decoding at a relay node, without investigating interference mitigation in the relay assignment. Ju et al. [12] considered a cooperative network in the presence of multiple interferers at the destination based on maximum mutual information on both DF-based and AF-based schemes. However, the paper just focuses on outage probability without the description of the best relay selection process, which is important to prevent from collision between relay nodes. In addition, Krikidis et al. [14] investigated the behavior of max–min-based relay selection schemes for ad hoc networks with inter-cluster interference. It is assumed that AF relaying scheme is used at each node and a direct link between source and destination is not available in the cluster. Whereas our work considers DF relaying scheme and a relay selection process is needed only if the direct link is failed. Moreover, communication in each cluster is based on orthogonal channels which is basically different from our model. An important difference between the models in [14] and our study is that the relay selection in [14] based on channel quality is performed at PHY layer without considering the interference limitation. Otherwise, the proposed scheme taking into account channel quality and the queue length at each relay focuses on DF scheme at MAC layer under consideration the impact of interference caused by relay selection.

3 System model

3.1 Assumptions

In this paper, the relaying method relies on regenerative cooperation in which the potential relays attempt to detect and recover the original message from the source before forwarding the decoded bits toward the destination. We make the following assumptions: (1) the fading channels between nodes are flat in frequency and quasi-static Rayleigh; (2) the channel is reciprocal; i.e., the channel from i to j is the same as the channel from j to i; and (3) the CSMA/CA scheme is used for random access, and the carrier sensing range is twice the transmission range.

3.2 Signal-to-interference-noise ratio and channel capacity

Let P_i be the received signal power at receiver j from source i, P_k be the interference power of other signals at j from the surrounding nodes, and N is the noise power (all in watts). $N_{nbr}(j)$ denotes the set of surrounding nodes of j. Then the received signal-to-interference-plus-noise ratio ($SINR$) at j on each link $i-j$ is given by:

$$SINR(i,j) = \frac{P_i}{N + \sum_{k \neq i} P_k} \quad (i, k \in N_{nbr}(j)). \tag{1}$$

We utilize the concept of the information-theoretic capacity to evaluate the transmission efficiency of the cooperative scheme. The channel capacity of each link $i-j$ calculated at j represents the upper bound on the amount of information that can be transmitted successfully over a communication channel. This is an effective method for approximating the link efficiency in wireless systems, without the requirements of complex coding, detecting, and decoding procedures [27]. For a continuous-time noisy-channel with limited bandwidth W [Hz], which is corrupted by an additive white Gaussian noise (AWGN) with power spectral density $N_0/2$ [W/Hz], the capacity of a Gaussian channel assuming a finite bandwidth at the receiver side related to the SINR by Shannon's theorem is

$$C(i,j) = W \log_2\left(1 + \frac{P_i}{N_0 W + \sum_{k \neq i} P_k}\right), \tag{2}$$

where $C(i, j)$ is measured in bits per second. This value is then compared with the required rate R_{req}. A packet is considered to be received successfully if the instantaneous channel capacity satisfies the required rate. Otherwise, the receiver will broadcast a failure feedback to its neighbors.

4 Description of the proposed cooperative scheme

This paper focuses on multi-hop wireless networks with a proactive traffic-aware routing protocol—TADR [20], which uses the concept of potential in physics to reduce congestion and improve the overall throughput. By combining cooperative communication and a background routing algorithm, we arrive at a reliable and traffic-aware cooperative scheme to significantly improve the network performance. Each node maintains a list of its neighbors with the hop count toward the final destination (sink), which is useful to limit the number of neighbors joining in the contention phase. The specific operation of the cooperative scheme, which is also illustrated in Fig. 2 is as follows:

4.1 Source transmission

The source node denoted by s sends the data packet toward its surrounding nodes with power P. All neighbors receive and estimate the *SINR* of the incoming packet.

4.2 Relay and destination checking

All neighbors, including the relays r and the destination d, receive the packet and calculate the respective channel capacity. If this value exceeds the required rate, an acknowledgment (ACK) frame is broadcast by the destination to all the surrounding nodes with the ID of the respective data packet. Then the potential relays recognize that the message has been received at the destination successfully, and they remove the packet message from their buffer because more transmissions from the relays are not necessary. Otherwise, the destination sends an NACK packet and moves to the next phase. It is noted that in SR scheme, relay selection is done before the source sends the packet. The best relay then always retransmits the packet without considering the packet decoding at the destination which may cause inefficiency. Whereas, IR scheme is based on ACK/NACK to retransmit the packet but without considering channel condition.

4.3 Relaying contention

The source and destination maintain the set of their neighbors, given as N_s and N_d, respectively. The relay candidate set N is denoted by $N = N_s \cap N_d + \{s\}$. Since a set of nodes contends together for the right to transfer the packet after receiving an NACK packet from the destination, this can cause collisions on the wireless channel, which reduces the channel utilization efficiency. Thus, only common neighbors of both the source and the destination participate in the relaying assignment process to reduce the contention area, as depicted in Fig. 1. The source also has the opportunity to retransmit the packet if it wins the competition with other relays. Similar to the destination, the relays also receive the message from the source in the first phase. If the calculated channel quality satisfies the threshold that meets the system data rate, the packet will be stored in reserve for the relay assignment, or it will be removed if the first transmission to the destination is successful.

In the adaptive IR scheme with instantaneous channel estimation based on the received ACK, NACK increases the reliability of transmission. The destination can decide to cooperate or not, depending on the packet reception. Then, each overhearing relay having the estimated capacity that satisfies the required rate will calculate a waiting period for its own timer t_i, following Eq. (3):

$$t_i = \frac{k}{\rho_i(L - q_i)} = \frac{k}{\rho_i \overline{q_i}}, \tag{3}$$

where ρ_i is *SINR* on the link from the destination to relay i. Whereas L, q_i and $\overline{q_i}$ are maximum queue length, current, and remaining queue length of the transmitting buffer of each relay $(q_i, \overline{q_i} \in [0, L])$, respectively. We let k be a heuristic parameter that is used to adjust the timer value if needed. The unit of k depends on the units of both ρ_i and $\overline{q_i}$. Here, ρ_i is a scalar, whereas $\overline{q_i}$ has the unit of *packets*. Therefore, k has the unit of *seconds.packets* (Fig. 2).

Each potential relay i starts its own timer with an initial value t_i that is inversely proportional to the CSI and current traffic at each relay. Without considering the effect of collisions at the MAC layer, the best relay with the largest product of channel quality and the remaining queue length will expire first and win the contention after a minimum period of T_b s. One of the relay is not always selected as the best relay node. Because the best relay is chosen at each hop based on relaying contention phase, which combines both channel quality and remaining queue length at the local node. It is possible that the relay can be chosen once again; however, it is not always. The best relay sends a short duration packet, called *Flag_RTS* to notify this event to the neighboring nodes. The other relays rely on this flag packet to give up the contention phase and are in listening mode. Then, the winner may retransmit the message. However, for the special case that some relays are in

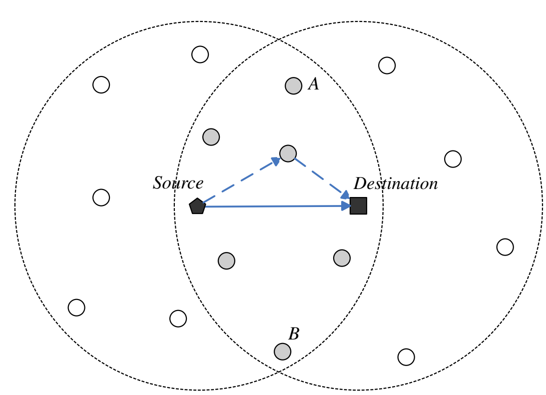

Fig. 1 The best relay selection from the standpoint of each source–destination pair. The potential relays are *gray* nodes in the common area in the transmission range of the source and destination

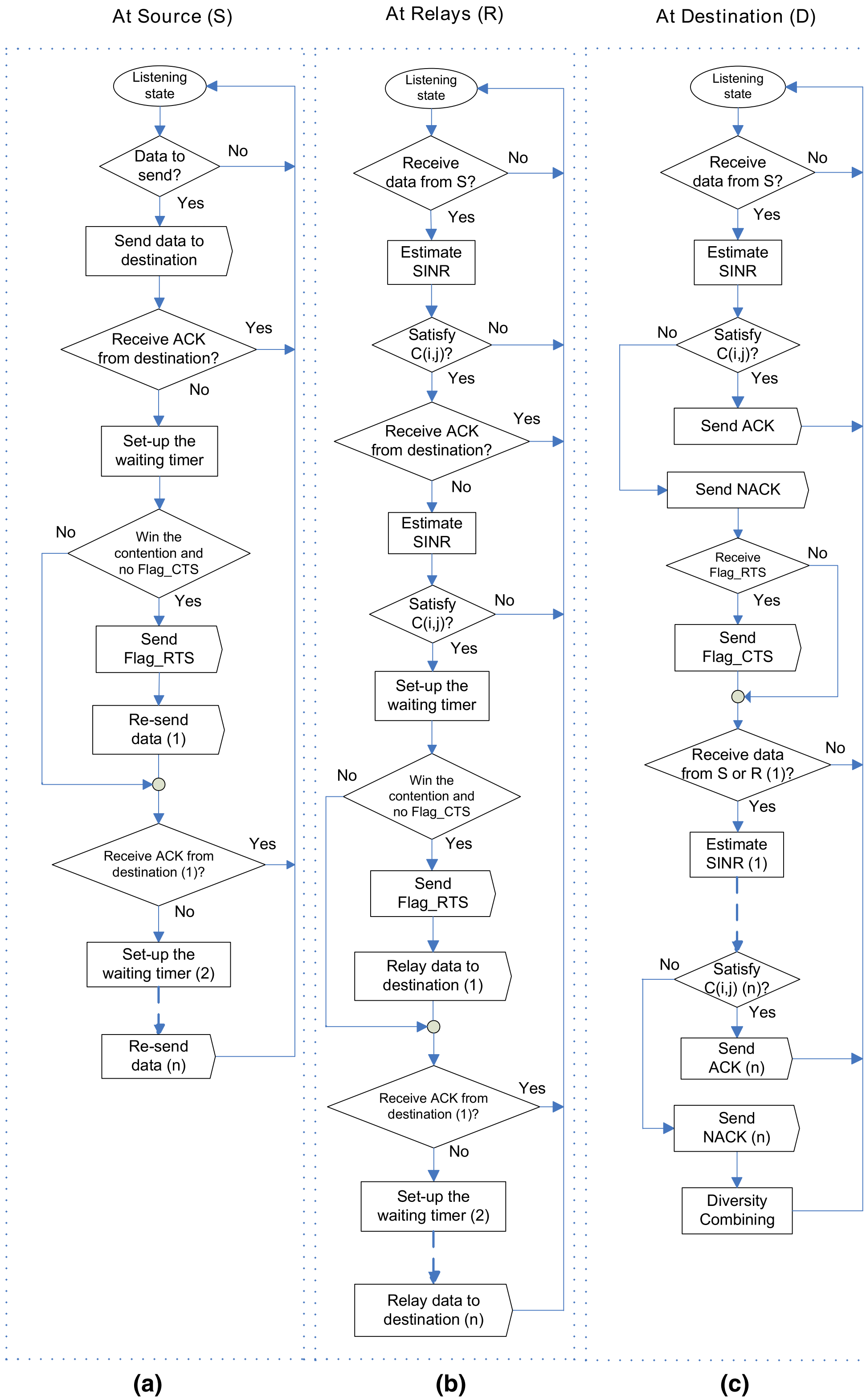

Fig. 2 Flowchart of the relay assignment scheme: (**a**) source, (**b**) relays, and (**c**) destination

hidden state from each other (i.e., they cannot listen each other), the destination needs to notify all relays with another short duration packet (*Flag_CTS*) to reduce unnecessary transmissions from the other relays. The queue length is used as follows in the relay selection: if a node has more packets in the queue, it has lower priority to become a relay node for another source–destination pair. The node then can transmit its own packets sooner when it is a source node. The relaying model is opportunistic because the best relay is chosen at each hop based on recalculation after relaying contention phase. The best relay selection can be executed many times depending on the successful reception and the ACK packet from the destination. We set the maximum number of tries for the best relay selection to 3 as a parameter in simulation settings.

4.4 Destination combining

At the destination, if the packet from the source is received successfully, an ACK packet is sent to confirm successful reception. Otherwise, an NACK packet is broadcast, and the relay assignment phase starts as in the second step. The destination also stores the packet for further combining. Once the incoming packet is received successfully, it is forwarded to the next hop. However, in the worst case, when all retransmission attempts have failed, the destination will use the maximal ratio combining technique [5] to try to recover the original packet from the previous replicas. This requires more complicated hardware; however, it significantly reduces the packet dropped ratio due to faults on the wireless channel.

5 Probabilistic analysis of the proposed relay assignment scheme

In this section, we analyze the failure probability of the proposed cooperative scheme in view of a one-hop network with a source, a destination, and a group of relay nodes. The analysis is referred to the work in [4]. The failure of the relay assignment scheme occurs since there is more than one relay that becomes the best relay and retransmit the same packet to the destination within the same time interval c which causes by the switching time and the propagation delay. This degrades the system performance and efficiency because of the collision and redundancy.

5.1 Cases of failure

Based on the operation of the proposed relay assignment scheme, we consider two cases of failure: (1) all relay candidates N can listen each other and (2) some relays in set N are hidden from each other (e.g., node A and node B in Fig. 1). Figure 3 describes the two cases, respectively. It is noted that the cooperative scheme is occurred after the NACK packet from the destination. Then, the flag packets are sent by the best relay and the destination to confirm the winner of the relay contention.

For the case of no hidden relays (Case 1), the collision between the best relay timer T_b and two or more relays can happen during the time interval c, depending on the propagation delay needed for signals to travel in the wireless channel and the radio switch time from receive-to-transmit mode (Eq. 4). On the other hand, for the case of hidden relays (Case 2), the interval c is increased by the duration of the flag packet from the best relay and the propagation delay on the destination–relay links, as well as the radio switch time at the destination (Eq. 5). The interval c can be considered as the overhead period caused by the wireless medium. The higher this interval conducts the higher the probability of collision between the best relay and the others. Therefore, we assess the maximum value of c in both cases.

1. No hidden relays (Case 1)

$$c = |t_b - t_i|_{max} + d_{rr_{max}} + d_{sw}, \tag{4}$$

2. Hidden relays (Case 2)

$$c = |t_b - t_i|_{max} + d_{rr_{max}} + 2d_{sw} + t_{dur} + 2d_{rd_{max}}, \tag{5}$$

where t_b and t_i, the time that the best relay and other relays i start their timers, respectively; d_{rr}, propagation delay between two relay nodes. $d_{rr_{max}}$ is the maximum value; d_{rd}, propagation delay between relay i and destination d. $d_{rd_{max}}$ is the maximum value; d_{sw}, receive-to-transmit switch time of each radio; t_{dur}, the duration of flag packet (Flag_RTS) which is transmitted by the best relay.

Let T_b $(\min\{T_i\})$ be the best relay timer and T_i be the other relay timers. Then, the probability of collision between two or more potential relays within the same interval c can be written as follows:

$$Pr(collision) = Pr(any\ T_i - T_b < c|\ i \neq b, i \in N). \tag{6}$$

Let $U_1 < U_2 < \cdots < U_N$ be the ordered random variables $\{T_i\}$, where the minimum timer T_b is equivalent to U_1 and U_2 is the second minimum timer, then

$$Pr(any\ T_i - T_b < c|\ i \neq b, i \in N) \equiv Pr(U_2 < U_1 + c). \tag{7}$$

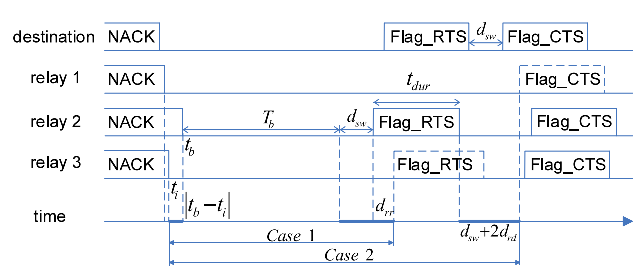

Fig. 3 Illustration for failure probability. Assume that relay 2 is the best relay, relay 3 is a no-hidden relay, and relay 1 is a hidden relay

Given that $U_i = \frac{k}{\rho_i \overline{q_i}}$, then $U_1 < U_2 < \cdots < U_N$ is equivalent to the timer values $\frac{k}{\rho_1 \overline{q_1}} < \frac{k}{\rho_2 \overline{q_2}} < \cdots < \frac{k}{\rho_N \overline{q_N}}$. Moreover, it is noted that the SINR ρ_i is mainly proportional to the power of channel response $|h_{i,j}|^2$ on the link between each relay i and destination node j. Equation (7) can thus be written

$$Pr(U_2 < U_1 + c) = Pr\left(\frac{1}{|h_{2,j}|^2 \overline{q_2}} < \frac{1}{|h_{1,j}|^2 \overline{q_1}} + \frac{c}{k}\right), \tag{8}$$

Then, the probability of failure can be calculated by Lemma 1 in [4]

$$Pr(U_2 < U_1 + c) = 1 - I_c \tag{9}$$

$$I_c = N(N-1)\int_c^\infty f(u)[1-F(u)]^{N-2} \times F(u-c)du, \tag{10}$$

where $F(u)$ and $f(u)$ are the cumulative distribution function (CDF) and probability density function (PDF) of the timer functions T_i of the N relays, respectively.

5.2 Probabilistic analysis

To calculate the probability in Eq. (10), we need to calculate the probabilistic functions of the timer T_i. The CDF and PDF of each T_i are respectively given by

$$F(t) = Pr[T_i \le t] = 1 - CDF_{|h_i|^2\overline{q}}\left(\frac{k}{t}\right), \tag{11}$$

$$f(t) = \frac{d}{dt}F(t) = \frac{k}{t^2}PDF_{|h_i|^2\overline{q}}\left(\frac{k}{t}\right), \tag{12}$$

where $cdf_{|h_i|^2\overline{q}}$ and $pdf_{|h_i|^2\overline{q}}$ are the CDF and PDF of the product function between channel response and the remaining queue length. In order to find the distribution of the production distribution, we conduct the probabilistic function of each separate distribution.

5.2.1 *Fading channel*

Assuming that the wireless channel is affected by Rayleigh fading due to multi-path reflection, the channel gain $|h_{r,d}|$ between the relay and the destination follows the Rayleigh distribution and its power $|h_{r,d}|^2$ follows the exponential distribution. The CDF and PDF of the exponential variables with parameter $\lambda > 0$ are given by [10]

$$F_X(x) = 1 - e^{-\lambda x}\ (x \ge 0), \tag{13}$$

$$f_X(x) = \lambda e^{-\lambda x}\ (x \ge 0). \tag{14}$$

5.2.2 *Queue model*

For a simplicity, the analysis is based upon M/G/1 queues which receive packets based on a Poisson arrival process with arrival rate λ_s packets/sec and average service time $\overline{x}$ depending on the channel access mechanism [6, 19]. The thorough analysis of queueing model is beyond the scope of this paper. The main objective of this section is to evaluate the failure probability of the relay assignment scheme considering the arrival rate and service rate as parameters. The detail queueing analysis will remain an important part of future work. Since the exact queue length distributions were significantly more complex than the two-moment approximation, we follow a simple approximation for the M/G/1 queue length distribution in [17] which depends only on the first and second moments of the service time distribution. The PMF of the remaining queue length distribution are respectively given by (see "Appendix 2")

$$P[\overline{N} = k] = P[N = L-k] \approx U_0\alpha^{L-k-1}(1-\alpha), \tag{15}$$

for $k = 0, 1, 2, \ldots, L-1$ and $P[\overline{N} = L] = 1 - U_0$. Where U_0 is the server utilization, $U_0 = \lambda_s\overline{x}$.

5.2.3 *Distribution of the timer functions*

From the probabilistic distribution of each random variable, we obtain the joint CDF and PDF of the product of the above random distributions $|h_i|^2\overline{q}$ from "Appendix 1" by substituting Eqs. (13) and (15) into Eqs. (19) and (20). Then, Eqs. (11) and (12) become

$$F(t) = 1 - \Big[U_0\alpha^{L-1}(1-\alpha) + \sum_{y=1}^{L-1} U_0\alpha^{L-y-1}(1-\alpha)\left(1 - e^{-\lambda\frac{k}{yt}}\right) + \left(1-U_0\right)\left(1 - e^{-\lambda\frac{k}{Lt}}\right)\Big], \tag{16}$$

$$f(t) = \frac{k}{t^2}\left[\sum_{y=1}^{L-1}\frac{1}{y}U_0\alpha^{L-y-1}(1-\alpha)\lambda e^{-\lambda\frac{k}{yt}} + (1-U_0)\lambda e^{-\lambda\frac{k}{Lt}}\right]. \tag{17}$$

The probability of failure is now calculated by substituting the above two equations into Eq. (10) with the average value of any channel coefficient $\lambda = E[|h_{i,j}|^2] = 1$ and $N = 7$ nodes. Besides, other parameters such as U_0, L are set to 0.85 and 100, respectively.

5.3 Results

It is seen in Eq. (8) that the collision probability reduces with the increase of k. However, k cannot be arbitrarily large, since it increases the time needed for each source to find out the best relay. Therefore, there is a trade-off between the collision probability and the speed of relay selection. From the integral in Eq. (10), the collision probability is a function of k/c. The results are plotted in Fig. 4 for various values of k/c with the server utilization $U_0 = 0.85$.

Assume that distance between network nodes is <100 m. Whereas typical switching time should be <5 µs [16], which results in $c \approx 20\,\mu s$. For instance, in case of $U_0 = 0.85$, the collision probability is kept below 1 % since k approximates 52×10^{-6}. Table 1 shows the list of k to keep the probability of collision <1 % according to a range of the server utilization U_0.

6 The impact of relay assignment interference

An inappropriate relay assignment may interfere with the transmission of the other nodes, leading to inefficiency We demonstrate with an example that relay assignment can cause interference that negatively affects the network performance. In Fig. 5, it is assumed that there are three source–destination pairs where transmission occurs simultaneously. Three dashed circles show the transmission ranges of the three relay nodes r_2, r_3, and r_5.

If the impact of relay assignment interference is negligible, the three source–destination pairs can choose r_1, r_2, and r_5 as relay nodes for their packet transmissions. However, the relay assignment for each transmission pair can cause interference to the others. Hence, an improvement in the network performance using cooperative communication may not be achieved. For instance, in this case, destination d_1 is within the transmission range of r_2. Therefore, the transmission of r_2 will disturb the reception of d_1. Moreover, if r_3 and r_5 simultaneously transmit packets as relay nodes for $s_2 - d_2$ and $s_3 - d_3$ pairs, respectively, the collision can reduce the network capacity. Thus, the feasible relays for these source–destination pairs should be r_1, r_3, and r_6, respectively. Therefore, interference mitigation needs to be considered. The relay nodes should be chosen by taking both the relay interference and channel conditions into account.

This study endeavors to solve the problem by building at each node a table with the connection status of its neighboring nodes by overhearing their transmission. Each respective neighbor is set to interfering status if it is in transmission/reception with other nodes. Otherwise, the status is non-interfering. Each potential node has to check its table prior relay contention to know whether it may cause interference for other transmission or not.

Table 1 List of k according to a range of U_0

U_0	0.6	0.65	0.7	0.75	0.8	0.85	0.9
k/c	6.91	6.1	5.29	4.43	3.49	2.58	1.93
$k(\times 10^{-6})$	138	122	106	89	70	52	39
Prob. $(\times 10^{-3})$	5.1	5.6	7.6	4.2	7.3	5.6	4.3

7 Performance evaluation

7.1 Simulation setup

The performance of the proposed scheme is evaluated by simulation using OPNET Modeler 16.0 and compared with two schemes: (1) the original traffic-aware routing scheme in

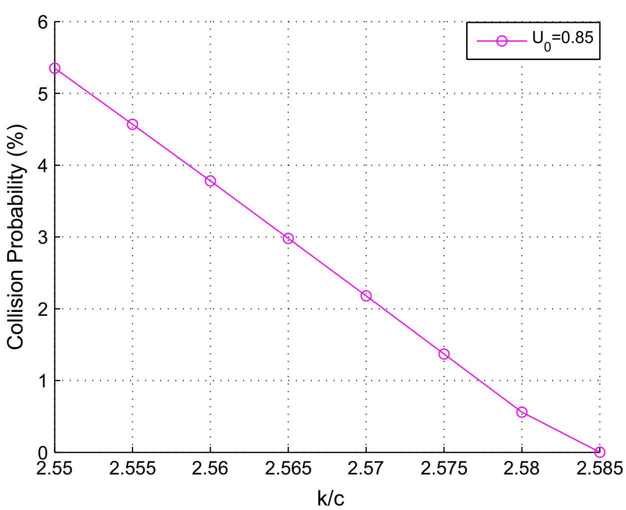

Fig. 4 The probability of collision versus various values of k/c in the case $N = 7$ and $U_0 = 0.85$

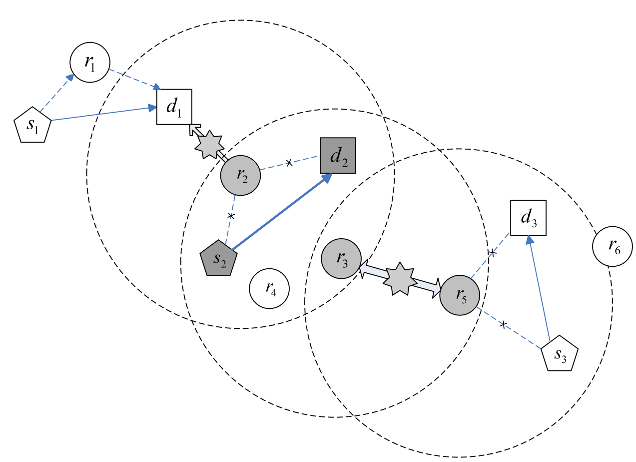

Fig. 5 Two cases of relay assignment interference: (1) relay r_2 interferes $s_1 - d_1$ transmission and (2) two relay nodes $r_3 - r_5$ mutually interfere each other

[20] without cooperative nodes (direct transmission) and (2) the best relay scheme based on only channel estimation [4] (the best relay scheme). We adapt the standard IEEE 802.11 MAC protocol for the proposed scheme. We also make some modifications to the physical layer. If the calculated channel capacity from the received signal $C(i, j)$ satisfies the requirement, the PHY layer will pass the signal to the MAC layer with the respective *SINR*. The relay assignment process is executed at the MAC layer. The simulation parameters for the routing protocol are as specified in [20]. A total of 50 nodes are deployed randomly within a coverage range of 300 m × 300 m. Each node generates traffic with a packet length of 500 bytes according to a exponential inter-arrival time. We set a value of k around 100×10^{-6}. The transmission range is set to 60 m, and the data rate is 2 Mbps. The initial energy of every node is assumed to be 10 J. The detailed simulation parameters are listed in Table 2. We compared the performance of the three schemes under three metrics: the PDR, average energy consumption per bit, and end-to-end packet delay.

7.2 Numerical results

7.2.1 PDR

The PDR is defined as the total number of packets received at the sink divided by the total number of packets transmitted by all the sender nodes. Figures 6 and 7 show the PDR versus various packet inter-arrival times and the number of network nodes, respectively. We see that with an increase in network traffic, i.e., a smaller value of the packet inter-arrival times, the PDR is reduced in all three schemes. Similarly, an increase in the number of network nodes also reduces the number of received packets at the sink. This is because the higher traffic produces more collisions and interference for the surrounding nodes, which cause packets to be dropped. Besides, higher packet loss also derives from the channel congestion and overloaded nodes due to multiple traffic flows which directed to them relating the operation of routing protocols. Nevertheless, in all situations, the proposed scheme always obtains a higher PDR than the other schemes. It improves the possibility of receiving packets successfully by retransmitting them via the potential relay and combining them at the destination. Furthermore, an advantage of the proposed scheme in comparison with the best relay scheme is that our scheme takes into account the effects of interference caused by the relay assignment.

7.2.2 Energy consumption

The energy model is referred to in [7]. The transmit, receive, and idle power are 150, 110, and 95 mW,

Table 2 Simulation parameters

Parameter	Value
Deployment type	Random topology
Deployment area	300×300 m^2
Number of nodes	50
MAC protocol	CSMA/CA MAC for 802.11
Carrier frequency	2.4 GHz
Transmission range	60 m
Packet size	500 bytes
Data rate	2 Mbps
Simulation time	1,000 s
Traffic types	Exponential inter-arrival time

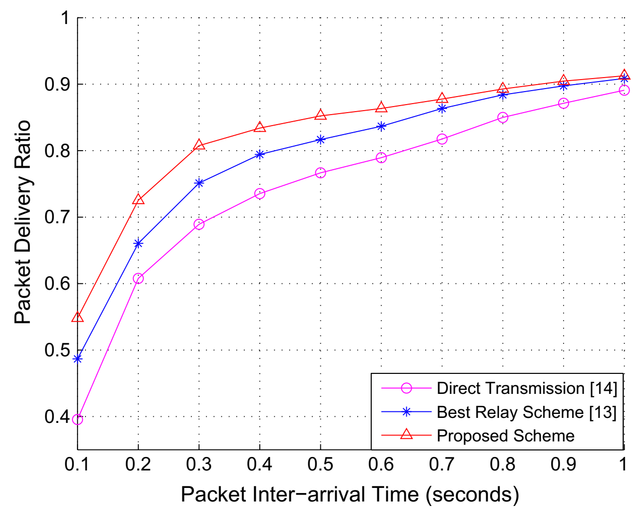

Fig. 6 PDR with respect to packet inter-arrival times

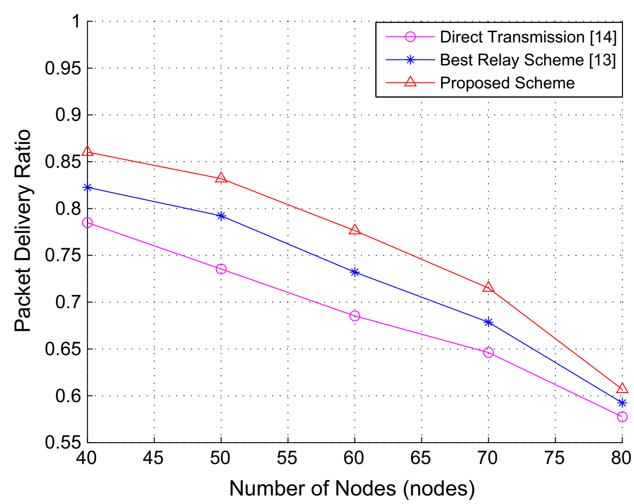

Fig. 7 PDR with respect to the number of network nodes with a exponential packet inter-arrival time of 0.4 s

respectively. The sleep power is ignored because of the absence of a power-saving strategy in our model. In Fig. 8, we plot the average energy consumption per bit versus various packet inter-arrival times. The increasing traffic at each node increases packet collisions. This means that more energy is required for retransmissions or relay selection. It is observed that as compared with direct transmission, both cooperative schemes achieve a significant improvement in terms of energy savings. This is because the relay node that retransmits is the one having a better channel state relative to the destination. In particular, the proposed scheme outperforms the best relay scheme because it enjoys the advantage of cooperative communication and thus combines both the instantaneous channel status and interference mitigation, which significantly affects the relay utilization efficiency since the network traffic increases. Moreover, the proposed scheme reduces unnecessary transmission from the best relay once the destination successfully decodes the packet from the source for the first time.

7.2.3 End-to-end delay

We also compare the overall packet delay between the three schemes under an increase in network traffic. The end-to-end delay is accounted for packets that are received properly at the sink. As shown in Fig. 9, higher traffic results in higher packet delay. However, the proposed scheme always exhibits shorter packet delays than the other schemes because the relay selection in the proposed scheme uses the channel state information and combined SR/IR, and the packet is forwarded to the next hop without waiting for relay selection if direct transmission is successful. Moreover, considering the queue length of each potential relay in the relay contention allows the relay with a lower queue length to retransmit, which reduces the overall packet delay. However, in case of low traffic in which the effect of interference and collisions is reduced, the packet can be retransmitted by the source with high reliability and short delay. Whereas, in the proposed scheme, the feedback based on *Flag_RTS/Flag_CTS* after each relay contention and destination-combining at the destination can cause more delay.

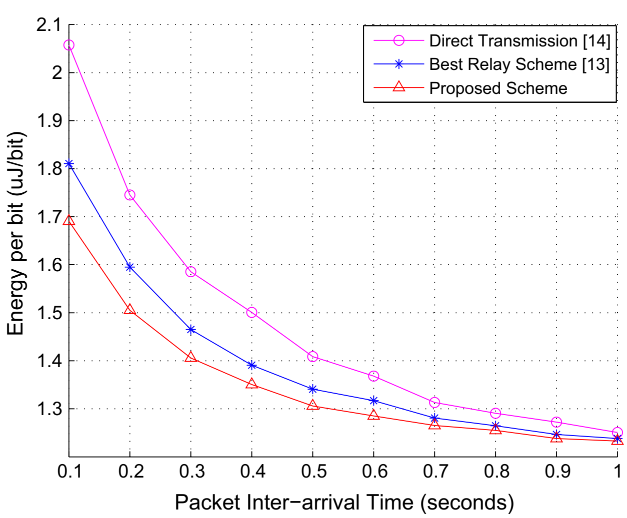

Fig. 8 Energy consumption per bit with respect to packet inter-arrival times

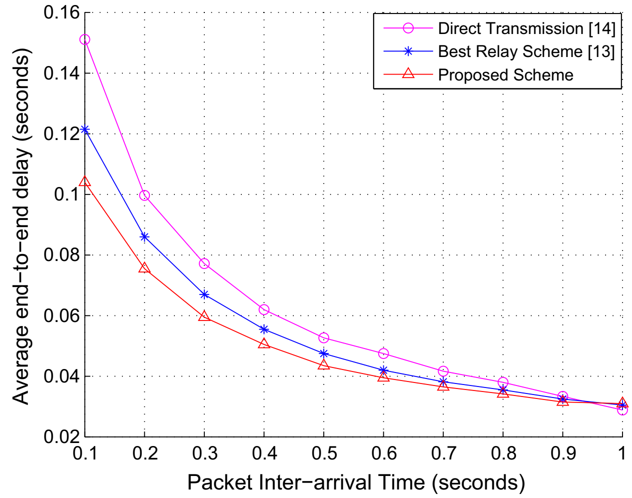

Fig. 9 Average end-to-end delay with respect to packet inter-arrival times

8 Conclusions

In this paper, we presented a reliable and traffic-aware relay assignment scheme for multi-hop wireless networks, where the DF relay scheme at the physical layer and the relay assignment process at the MAC layer are incorporated with the objective of enhancing network performance. The relay assignment scheme combines the SR and IR schemes from the destination based on the channel state information and current queue length.

We plan to pursue the following directions in our future work: (1) we intend to reduce the collision probability between feedback and data packets via more effective scheduling strategies; (2) the proposed scheme relies on a given source–destination pair at each hop, so global optimization cannot be achieved; we plan to extend our current scheme in view of a joint design with the routing protocol closely in order to improve control packet and global optimization; and (3) we believe that a performance analysis based on Markov chains and the queuing model for the relay assignment process will be a promising extension.

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Appendix 1: Products of a continuous and a discrete random variables

Let X be a continuous random variable with known PDF $f_X(x)$. Let also Y be a discrete random variable with PMF $P(Y=y)$ which is defined on the interval $[0, L]$ $(L>0)$. The CDF of $U=XY$ is given by

$$F_U(u) = P(XY \leq u) = \sum_{y=0}^{L} P(Y=y)P(yX \leq u | Y=y), \tag{18}$$

where $P(yX \leq u | Y=y) = P(X \leq \frac{u}{y} | Y=y) = F_X(\frac{u}{y})$ with $y>0$. On the other hand, $P(0X \leq u | Y=0) = 1$ for $u \geq 0$ or $P(0X \leq u | Y=0) = 0$ for $u<0$. With $u \geq 0$, Eq. (18) reduces to

$$F_U(u) = P(Y=0) + \sum_{y=1}^{L} P(Y=y)F_X\left(\frac{u}{y}\right). \tag{19}$$

However, a continuous and a discrete random variables don't have a joint PDF because their joint distribution is not absolutely continuous in 2-dimensional plane. We make the following estimation

$$f_U(u) \approx \frac{d}{du}F_U(u) = \sum_{y=1}^{L} \frac{1}{y} P(Y=y) f_X\left(\frac{u}{y}\right). \tag{20}$$

Appendix 2: Approximation for the M/G/1 queue length distribution

Consider an M/G/1 queue with average service time $\bar{x}$, Poisson arrival rate λ, and a squared coefficient of variation of service time c_x^2. The probability that there are at least $k+1$ packets in the queue is given by [17]

$$P[N > k] \approx U_0 \alpha^k, \quad k = 0, 1, 2, \ldots, L-1. \tag{21}$$

where U_0 is the server utilization ($P[N>0] = U_0$, $P[N=0] = 1 - U_0$) and $\alpha = \frac{U_0(c_x^2+1)}{2+U_0(c_x^2-1)}$ $(\alpha \leq 1)$. Then, the CDF of queue distribution can be written as follows

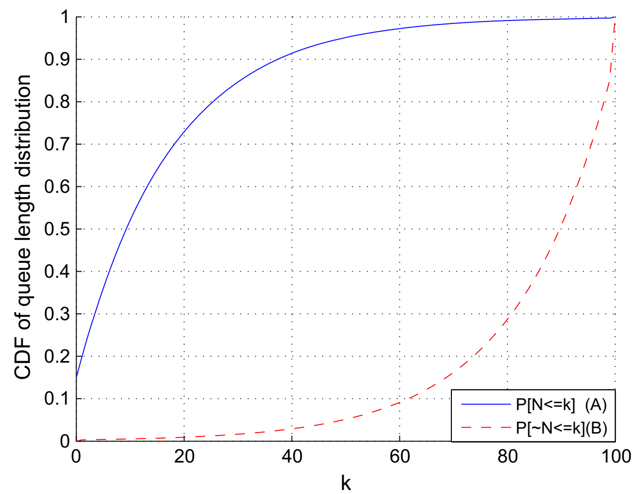

Fig. 10 Approximation CDF for current occupied queue length distribution (*line A*) and remaining queue length distribution (*line B*)

$$P[N \leq k] = 1 - P[N > k] \approx 1 - U_0 \alpha^k. \tag{22}$$

for $k = 0, 1, 2, \ldots, L-1$, and $P[N \leq L] = 1$. The PMF of queue distribution is given by

$$\begin{aligned} P[N = k] &= P[N > k-1] - P[N > k] \\ &\approx U_0 \alpha^{k-1}(1-\alpha), \quad k = 1, 2, 3, \ldots, L. \end{aligned} \tag{23}$$

From queue length distribution, the PMF and CDF of the remaining queue length distribution can be given by

$$\begin{aligned} P[\overline{N} = k] &= P[N = L-k] \\ &\approx U_0 \alpha^{L-k-1}(1-\alpha), \end{aligned} \tag{24}$$

for $k = 0, 1, 2, \ldots, L-1$ and $P[\overline{N} = L] = 1 - U_0$.

$$\begin{aligned} P[\overline{N} \leq k] &= P[N \geq L-k] \\ &= P[N > L-k] + P[N = L-k] \\ &\approx U_0 \alpha^{L-k} + U_0 \alpha^{L-k-1}(1-\alpha), \end{aligned} \tag{25}$$

for $k = 1, 2, \ldots, L-1$ and $P[\overline{N} \leq 0] = P[N = L] = U_0 \alpha^{L-1}(1-\alpha), P[\overline{N} \leq L] = 1$.

The CDF calculated by Eqs. (24) and (25) conduct different results because of the estimation in Eq. (21). For instance, $k=2$, then the probabilities $P[\overline{N} \leq 2]$ calculated by these equations are respectively

$$\begin{aligned} P[\overline{N} \leq 2] &= P[\overline{N} = 0] + P[\overline{N} = 1] + P[\overline{N} = 2] \\ &\approx U_0(1-\alpha)(\alpha^{L-1} + \alpha^{L-2}) + U_0 \alpha^{L-3}(1-\alpha), \\ P[\overline{N} \leq 2] &= P[N > L-2] + P[N = L-2] \\ &\approx U_0 \alpha^{L-2} + U_0 \alpha^{L-3}(1-\alpha). \end{aligned}$$

The difference is that $(1-\alpha)(\alpha^{L-1} + \alpha^{L-2}) = \alpha^{L-2} - \alpha^L \neq \alpha^{L-2}$. However, when the server utilization $U_0 < 1$, then $\alpha < 1$. For a large value of queue capacity L, α^L converges to 0. Therefore, the difference is negligible.

Figure 10 plots the approximation for queue distribution with $U_0 = 0.85, c_x^2 = 5$, and maximum queue length of 100 incoming packets.

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