Using Buffers in Trust Aware Relay Selection Networks with Spatially Random Relays

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Abstract—It is well recognized that using buffers in relay networks significantly improves the transmission reliability, which is often at the price of higher packet delay. Existing buffer-aided relay networks are all based on the physical links among cooperative nodes. This may however lead to performance degradation in practice, because that cooperative nodes may not trust each other for cooperation even though their physical connection are strong. In this paper, we propose a novel buffer-aided relay selection scheme to align data transmission with both strong and trusted links. By maintaining the buffer lengths as close as possible to the newly introduced target buffer lengths, the proposed scheme is able to balance the outage performance and packet delay. Both the outage probability and average packet delay are analyzed for spatially random relays. Particularly we show that outage performance may have error floors because of the trusts. The analysis shows that using buffers in trust aware relay networks is able to either increase the diversity order or lower the error floor of the outage probability.

Index Terms—Social trusts, buffer-added relay selection, stochastic geometry

I. INTRODUCTION

In traditional relay selection schemes, relays with strong physical links are selected for cooperative transmission. Because relays are mobile devices which are often handled by human users, the selected relay may not always be willing to help the transmission source. For example, a person is likely to use his/her mobile to help data transmission for his/her friends but not for strangers. Therefore, the effectiveness of cooperative transmission depends on not only physical links but also trusts among cooperative users. Exploring users' trusts in wireless networks has attracted much attention recently [1]–[3]. While various trust models (e.g. distance-based and rank-based trust models in [4], [5] respectively) have been proposed, the detail is beyond the scope of this paper. In this paper, we focus on how trusts (which are assumed to be available) are used to improve the relay selection. Social trusts can be represented either by binary values with 0 and 1 corresponding to no and full trust between two users respectively [2], or by a real value within $[0, 1]$ which represents the probability that two users are in trust [6]. In either case, only when a relay is in trust with the source transmitter, is it willing to join the cooperative transmission. This paper adopts the trust model in [6] as it describes a more general scenario. In relay selection networks, the difficulty is to decide whether a relay with strong links or high trusts shall be selected. In [6], the channel gains and trusts are incorporated into a single signal-to-noise-ratio (SNR) measurement and the relay with the maximum SNR is selected for cooperative transmission. While the selected relay can compromise between the channel gains and trusts, the full potential of the relay network is not fully released.

This is because both channel gains and trusts are uncorrelated random values. It is thus often that the selected relay is not in trust with the source when the corresponding links are strong, or the links are weak when the selected relay is in trust with the source.

On the other hand, buffer-aided schemes have attracted much recent attention in many research topics, i.e., cognitive radio networks [7] and physical layer security [8]. In [9], [10], novel buffer-aided adaptive link schemes have been proposed for 3-node relay networks, and the work was extended to bidirectional 3-node relay work in [11], [12]. Buffer-aided schemes can also work with space-time coding and network coding as is described in [13] and [14] respectively. In buffer-aided approaches, relays are able to store the data in buffers and hold the transmission until the corresponding links are strong enough, making it flexible for the cooperative transmission to align with 'strong' links. This encourages us to apply the buffers in trust aware relay networks, where the purpose is to better synchronize the transmission with both strong and trusted links. While various buffer-aided relay selection schemes have been proposed (e.g. [15], [16]), there is still large room for further improvement and none of them considers the trusts. Compared with their non-buffer aided counterparts, all buffer-aided schemes have coding gains which is 3dB for independent identical distributed (i.i.d.) fading channels [17], but not all of them have diversity gains. In principle, the diversity order of a relay selection system depends on the number of available links for selection. For a relay network with K relays, there are $2K$ links in total, but not all of them are always available for selection. To be specific, when the buffer of a relay becomes full or empty, the corresponding source-to-relay or relay-to-destination link is not available for selection respectively and so the diversity order is decreased by one. The max-link relay selection can achieve full diversity order of $2K$ but only when the buffer sizes are infinite and all channels are i.i.d. fading [16]. In practice, however, because the buffer sizes are always limited and/or the channels may not be i.i.d., the diversity order is often well below $2K$. When the trust is considered, even with i.i.d channels and infinite buffer sizes, the max-link can still not achieve full diversity. Because relay users often have different trusts with the source node, the probabilities to select different links are not the same (even for i.i.d. channels). This makes buffers more likely be empty or saturate, leading to diversity order lost.

Although applying buffers brings in coding and/or diversity gain, it also increases the packet delay because of the packet queuing at the buffers. In order to minimize the packet delay, the queues at the buffers shall be maintained as short as possible. This however contradicts the requirements for the diversity performance where the buffers shall avoid from being empty (or full). In [17], we proposed a delay reduced buffer-aided scheme, in which higher selection priority is given to relay-to-destination than to source-to-

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relay links, so data is moving out of buffers as quickly as possible to minimize the queuing lengths. While the proposed scheme in [17] significantly reduces the packet delay, it only has coding gain but little diversity gain.

In this paper, we propose a novel trust aware buffer-aided relay selection scheme which is able to balance the diversity gain and packet delay. This is achieved by introducing a new set of parameters, the 'target-queuing-lengths', from which the selection priorities are given to all available links. To be specific, by choosing appropriate target-queuing-lengths, the proposed scheme can be tuned to achieve minimum packet delay or maximum diversity order, or a compromise between the diversity and delay according to system requirements. The contribution of this paper is summarized as following:

- Propose a novel buffer-aided scheme which can balance the diversity and packet delay according to system requirements, where both physical links and trusts are considered (in Section III).
- Analyze the outage probability of the proposed scheme based on the random positions of the relays (in Section IV).
- Derive the average packet delay, diversity order and error floor of the proposed scheme (in Section V).
- Derive the optimum target buffer lengths for best outage performance and minimum average packet delay respectively (in Section VI).

II. SYSTEM MODEL

The system model of the buffer-aided relay network is shown in Fig. 1, where there are one source node S, one destination node D and K relay nodes R_k for $k = 1, \cdots, K$. We assume that relays are randomly positioned in the circular area A^1, where the centre of A is in the middle of the line connecting S and D, and the radius is r_o. Every relay is equipped with a data buffer of finite size L, and applies decode-and-forward (DF) protocol. We assume relay positions follow binomial position process (BPP). The BPP is often used to describe a group of fixed numbered nodes' random positions within an area [18], [19].
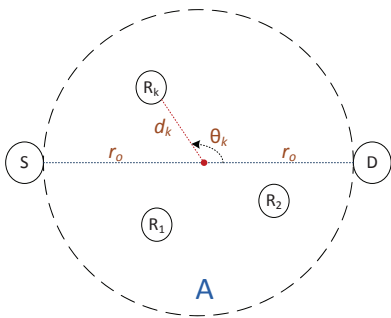

Fig. 1. System model for a relay network with one source, one destination and K relays randomly positioned in the area A.

In this paper, we assume the channels are independent and non identically distributed (i.n.i.d.) Rayleigh fading channels[2]. Thus the

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[1]The "circular area' assumption is for better exposition of the performance analysis, which is not required to apply the proposed scheme in practical systems.

[2]The Rayleigh fading assumption is for clear analysis and fair comparison with existing relay selection schemes since most of them also apply the same assumption. When other channel fading scenario such as the shadowing effect is considered, the proposed scheme can still be applied. Although the analytical expressions will be different from those for the Rayleigh fading, the improvement of the proposed scheme compared with existing schemes can still be similarly obtained.

SNR of $S \to R_k$ and $R_k \to D$ links are given by

$$\gamma_{s,r_k} = \frac{P_{tx}|h_{s,r_k}|^2}{\sigma_n^2 d_{s,r_k}^\alpha} = \frac{g_{s,r_k}}{d_{s,r_k}^\alpha}, \qquad \gamma_{r_k,d} = \frac{P_{tx}|h_{r_k,d}|^2}{\sigma_n^2 d_{r_k,d}^\alpha} = \frac{g_{r_k,d}}{d_{r_k,d}^\alpha}, \quad (1)$$

respectively, where h_{s,r_k} and $h_{r_k,d}$ are the Rayleigh fading coefficients, d_{s,r_k} and $d_{r_k,d}$ are the distances, α is the path loss factor, $g_{s,r_k} = P_{tx}|h_{s,r_k}|^2$, $g_{r_k,d} = P_{tx}|h_{r_k,d}|^2$, and σ_n^2 denotes the power of complex additive white Gaussian noise (AWGN) and P_{tx} is the transmission power which is assumed to be the same at every transmission node. We assume without losing generality that all noise powers are normalized to unit.

We assume Rayleigh fading gains $|h_{sr_k}|^2$ and $|h_{r_k,d}|^2$ are normalized i.i.d. exponentially distributed. Thus g_{s,r_k} and $g_{r_k,d}$ are also i.i.d. exponentially distributed with the average gain as $\bar{\lambda} = P_{tx}$. As is illustrated in Fig. 1, the position of relay R_k is represented as (d_k, θ_k), and we have

$$d_{s,r_k} = \sqrt{r_o^2 + d_k^2 - 2r_o d_k \cos(\pi - \theta_k)}$$
$$d_{r_k,d} = \sqrt{r_o^2 + d_k^2 - 2r_o d_k \cos(\theta_k)} \qquad (2)$$

It is clear from (2) that both d_{s,r_k} and d_{s,r_k} are functions of d_k and θ_k. Thus if two links correspond to the same relay node, their path losses are dependently distributed, so are their overall channel gains; otherwise, their path loss and overall channel gain distributions are independent. In both cases, because the Rayleigh fading gains are i.i.d. and positions of all relay nodes follow binomial position process, the overall channel gain distributions are all identical. We note that, if the relay nodes' position are fixed, all channel gains become independent, but they are usually not identically distributed as the relay nodes often have different distances to the source and destination nodes.

The trust level between the source S and relay R_k is represented by the weight P_{φ_k}, where $P_{\varphi_k} = P(\varphi_k(t) = 1)$ and $\varphi_k(t)$ is a binary parameter to indicate whether S and R_k are in trust at time t or not. At time t, only if $\varphi_k(t) = 1$, will R_k receive the data from S, otherwise R_k refuses to receive. Once the relay R_k receives one data packet from S and stores it in its buffer, it will always forward it to the destination at later time.

III. SELECTION RULE

At any time, the numbers of data packets in all relay buffers form a "state". If the relay number is K and buffer size is L, there are $(L+1)^K$ states in total. The i-th state vector is defined as

$$\mathbf{q}_i = [q_{i,1}, \cdots, q_{i,K}], \qquad i = 1, \cdots, (L+1)^K, \qquad (3)$$

where $q_{i,k}$ is the buffer queuing length at R_k at state $\mathbf{q}_i$. On the one hand, buffers shall avoid from being empty or full to achieve high diversity order; On the other hand, keeping buffers empty helps to minimize the packet delays. In order to trade off the diversity and delay performance, we introduce the target buffer length (denoted as Θ_k) at every relay node, and maintain the buffer queuing length as close to Θ_k as possible. This is achieved by giving higher priorities to links corresponding to buffer lengths further away from their respective target lengths. At any buffer state, once the priority orders for selection for all available are obtained, the proposed link selection rules are applied as following:

- Consider the link with highest priority first, or if multiple links have the same priority, consider the link with the highest SNR.
- If this link supports the target transmission rate and the corresponding relay and source are in trust (i.e. $\varphi_k(t) = 1$), select this link.

- Otherwise consider the link(s) with the next highest priority, and repeat this process until one link is selected, or outage occurs if no link can be selected.

Below we first give priority orders to all relay nodes, from which the priorities for all links are obtained. Supposing the buffer state is $\mathbf{q}_i$, the difference between target length and the corresponding buffer length is given by $\Delta_k = q_{i,k} - \Theta_k$. Then higher priority is given to relays with larger Δ_k. Particularly if $\Delta_x = \Delta_y$, relays R_x and R_y have the same priority. But if $\Delta_x = -\Delta_y > 0$, R_x is given higher priority order than R_y. This is because, while the buffer queuing lengths at R_x and R_y are at the same distance away from Θ_k, selecting R_x corresponds to reducing the buffer length, which again leads to lower delay.

From the above, we obtain the priority order of R_k which is denoted as $\mathcal{O}(R_k)$, where the m-th highest priority corresponds to $\mathcal{O}(.) = m$. Every relay R_k corresponds a pair of $S \to R_k$ and $R_k \to D$ links. At state $\mathbf{q}_i$, if only one of the pair of links is available, the priority order for this link is the same as that for the relay which is $\mathcal{O}(R_k)$. Otherwise, if both links are available, we have the following 2 cases:

- Case 1: $\Delta(R_k) \geq 0$. In this case, because the buffer length is longer than the target length Θ_k, it is preferable to move data out of buffer (rather than moving into it). Thus the priority order of the $R_k \to D$ link is set as same as that for the relay node which is $\mathcal{O}(R_k)$, and the priority order for the $S \to R_k$ link is set to the $\mathcal{O}(R_k)$-th from the last.
- Case 2: $\Delta(R_k) < 0$. Similarly, the priority order of the $S \to R_k$ link is set to $\mathcal{O}(R_k)$, and the priority order for the $R_k \to D$ link is the $\mathcal{O}(R_k)$ from the last.

A central control node, which can be either an independent node or among existing nodes, is used to make the selection decision. The central node requires the knowledge of all links' channel gains and trust values, but not the knowledge of the buffer states. This is because buffers can always start from empty and the central node can monitor the buffer states. Thus the implementation of the proposed scheme requires the same knowledge as most other relay selection schemes including the non-buffer-aided max-min scheme and the existing buffer-aided max-max [15] and max-link [16]) schemes.

Before leaving this section, Fig. 2 shows an example to set the link priority orders in a 5-relay-nodes network, where the buffer size is $L = 4$, the target buffer lengths are $\Theta_k = 2$, and the buffer state is $\mathbf{q}_i = [0, 2, 2, 3, 4]$. The relays are ordered as, from highest to lowest priority, R_5, R_1, R_4, R_2 and R_3 respectively. There are 8 available links and the priority orders for every available links are also shown in Fig. 2, where $link_m$ indicates the priority order for the corresponding link is m.

IV. OUTAGE PROBABILITY

We denote $\mathbf{A}$ as the $(L+1)^K \times (L+1)^K$ state transition matrix, where the entry $A_{ij} = P(\mathbf{q}_i|\mathbf{q}_j)$ which is the transition probability from state $\mathbf{q}_j$ to $\mathbf{q}_i$. Particularly A_{ii} is the outage probability at state $\mathbf{q}_i$. Below we derive the transition probability A_{ij} for $i \neq j$ and $i = j$, from which we obtain the outage probability.

A. Outage probability at state $\mathbf{q}_i$: $P_{out}^{\mathbf{q}_i} = A_{ii}$

At state $\mathbf{q}_i$, the outage occurs if all available links are in outage, and thus the outage probability is given by

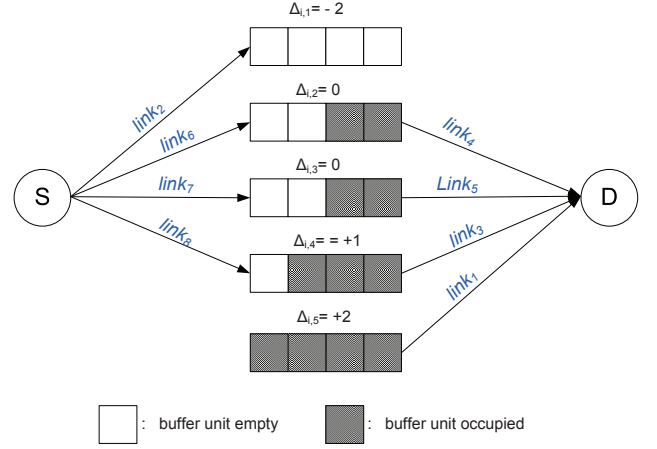$$P_{out}^{\mathbf{q}_i} = A_{ii} = P(out_1, \cdots, out_{N_i}) \qquad (4)$$

Fig. 2. An example of setting link priority orders: the target buffer length $\Theta_k = 2$.

where N_i is the number of available links at state $\mathbf{q}_i$, out_m is the event that $link_m$ is in outage, and $link_m$ is the link with the m-th priority order of selection. Because the channel gains for any two links are independent only if they correspond to different relay nodes, (4) can be decomposed into K terms, each corresponding to one relay node. We assume without losing generality that there are x relay nodes with both $S \to R_k$ and $R_k \to D$ links available, where these x pair of links are denoted as $(link_{a_1}, link_{a'_1}), \cdots, (link_{a_x}, link_{a'_x})$ respectively. The remaining $(K - x)$ relays nodes only have one of the $S \to R_k$ and $R_k \to D$ links available, denoted as $(link_{b_1}, \cdots, link_{b_{K-x}})$ respectively. Thus (4) can be expressed as

$$P_{out}^{\mathbf{q}_i} = \underbrace{P(out_{a_1}, out_{a'_1}), \cdots, P(out_{a_x}, out_{a'_x})}_{} \\ \times \underbrace{P(out_{b_1}), \cdots, P(out_{b_{K-x}})}_{}, \qquad (5)$$

In the following we derive $P(out_m)$ and $P(out_m, out_{m'})$.

1) $P(out_m)$: From (1), the link capacity for $link_m$ is given by $C_m = \log(1 + g_m/d_m^\alpha)$, where the subindex m corresponds for either a $S \to R_k$ or a $R_k \to D$ link. If $link_m$ is a $S \to R_k$ link, out_m occurs when either $C_m < \eta$, or S and R_k are not in trust (i.e. $\varphi_k = 0$), where η is the target data rate. If $link_m$ is a $R_k \to D$ link, out_m occurs only when $C_m < \eta$, because data will be forwarded to the destination once it is stored in a relay buffer. Thus we have

$$P(out_m) = \begin{cases} P_{\varphi_k} P(C_m < \eta) + (1 - P_{\varphi_k}), & link_m \in \{S \to R_k\} \\ P(C_m < \eta), & link_m \in \{R_k \to D\}. \end{cases} \qquad (6)$$

where $P(C_m < \eta)$ is given by

$$P(C_m < \eta) = \int_A P(C_m < \eta|R_k) p(R_k) dA \\ = \int_A P\left(\log\left(1 + \frac{|h_m|^2}{d_m^\alpha}\right) < \eta\right) p(R_k) dA \qquad (7)$$

where $P(C_m < \eta|R_k)$ is the probability for $C_m < \eta$ conditioned on the position of R_k, and $p(R_k)$ is the probability density function of position of R_k. Because relays follow binomial point process, we have $p(R_k) = 1/(\pi r_o^2)$. Then as is illustrated in Fig. 1, we have

$$P(C_m < \eta) = \frac{1}{\pi r_o^2} \int_{r=0}^{r_o} \int_{\theta=0}^{2\pi} (1 - e^{-\frac{d_m^\alpha \cdot \xi}{\lambda}}) r \, dr \, d\theta \qquad (8)$$

where $\xi = 2^\eta - 1$.

2) $P(out_m, out_{m'})$: We assume without losing generality that $link_m$ and $link_{m'}$ are the $S \to R_k$ and $R_k \to D$ links respectively. Considering both the line capacities and the trust, we have

$$P(out_m, out_{m'}) = P_{\varphi_k} P(C_m < \eta, C_{m'} < \eta) + (1 - P_{\varphi_k}) P(C_{m'} < \eta), \tag{9}$$

where $P(C_{m'} < \eta)$ can be obtained as in (8), and

$$\begin{aligned} P(C_m &< \eta, C_{m'} < \eta) \\ &= \int_A P(C_m < \eta | R_k) P(C_{m'} < \eta | R_k) p(R_k) dA \\ &= \frac{1}{\pi r_o^2} \int_{r=0}^{r_o} \int_{\theta=0}^{2\pi} (1 - e^{-\frac{d_m^\alpha \cdot \xi}{\lambda}})(1 - e^{-\frac{d_m^\alpha \cdot \xi}{\lambda}}) r dr d\theta \end{aligned} \tag{10}$$

B. Transition probability $A_{ji} = P(\mathbf{q}_j | \mathbf{q}_i, i \neq j)$

Suppose if $link_n$ (with n-th priority order) is selected, buffer state transits from $\mathbf{q}_i$ to $\mathbf{q}_j$. Without losing generality, we assume $link_n, link_{n+1}, \cdots link_{n+m}$ have the same priority order. Thus $link_n$ is selected if (1) all links with lower priority order than $link_n$ are in outage, (2) $link_n$ has the highest SNR among $link_n, \cdots, link_{n+m}$ links, and (3) $link_n$ is not in outage. Thus we have

$$\begin{aligned} A_{ji} &= P(link_n \text{ is selected}) = P(out_1, \cdots, out_{n-1}, \overline{out}_n) \\ &\times P(\gamma_n > \max\{\gamma_{n+1}, \cdots, \gamma_{n+m}\}), \quad i \neq j \end{aligned} \tag{11}$$

where $\overline{out}_m$ is the events that $link_m$ is not in outage.

We assume $link_n$ and $link_{n'}$ associate with the same relay node. If $link_{n'}$ is not available or has lower priority order than $link_n$, $link_{n'}$ does not appear in (11). Otherwise if $link_{n'}$ is available and has higher priority order than $link_n$, it appears in (11). Thus we have

$$\begin{aligned} A_{ji} = &\underbrace{P(out_{a_1}, out_{a_1'}), \cdots, P(out_{a_x}, out_{a_x'})}_{} \\ &\times \underbrace{P(out_{b_1}), \cdots, P(out_{b_y})}_{} \\ &\times P(\gamma_n > \max\{\gamma_{n+1}, \cdots, \gamma_{n+m}\}) \cdot B, \quad \text{for} \quad i \neq j \end{aligned} \tag{12}$$

where $B = P(out_{n'}, \overline{out}_n)$ or $B = P(\overline{out}_n)$ if $link_{n'}$ does or does not appear in (11) respectively, $link_{a_x}$ and $link_{a_x'}$ correspond to the same relay and all indices $\{a_x, b_y\} \in \{1, \cdots, n-1\}$.

While $P(\overline{out}_n) = 1 - P(out_n)$, $P(out_m)$ and $P(out_m, out_{m'})$ are obtained in (6) and (9) respectively. Below we drive $P(out_{n'}, \overline{out}_n)$ and $P(\gamma_n > \max\{\gamma_{n+1}, \cdots, \gamma_{n+m}\})$.

Following the similar procedure in deriving (6), we have

$$P(out_{n'}, \overline{out}_n) = \begin{cases} P_{\varphi_k} P(C_n < \eta, C_{n'} > \eta), \\ \qquad\qquad \text{if } link_n \in \{S \to R_k\} \\ P_{\varphi_k} P(C_n < \eta, C_{n'} > \eta) \\ + (1 - P_{\varphi_k}) P(C_{n'} > \eta), \\ \qquad\qquad \text{if } link_n \in \{R_k \to D\} \end{cases} \tag{13}$$

where $P(C_n < \eta, C_{n'} > \eta)$ is obtained as

$$\begin{aligned} P(C_n &< \eta, C_{n'} < \eta) \\ &= \int_A P(C_n < \eta | R_k) P(C_{n'} > \eta | R_k) p(R_k) dA \\ &= \frac{1}{\pi r_o^2} \int_{r=0}^{r_o} \int_{\theta=0}^{2\pi} (1 - e^{-\frac{d_n^\alpha \cdot \xi}{\lambda}}) e^{-\frac{d_{n'}^\alpha \cdot \xi}{\lambda}} r dr d\theta \end{aligned} \tag{14}$$

We have shown in Section II that channel gains are identical distributed. Furthermore, if multiple links have the same priority order, they must not correspond to the same relay node and thus

are also independent. Therefore, all links with the same priority order must have i.i.d. channel gains, and we have

$$P(\gamma_n > \max\{\gamma_{n+1}, \cdots, \gamma_{n+m}\}) = \frac{1}{m+1} \tag{15}$$

Finally the outage probability of the overall system is given by

$$P_{out} = \sum_{i=1}^{(L+1)^N} \pi_i \cdot p_{out}^{\mathbf{q}_i}, \tag{16}$$

where π_i is the stationary probability for state $\mathbf{q}_i$. Because the transition matrix $\mathbf{A}$ is column stochastic, irreducible and aperiodic, the stationary state probability vector is obtained as (see [20], [21]) $\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1} \mathbf{b}$ where $\boldsymbol{\pi} = [\pi_1, \cdots, \pi_{(L+1)^N}]^\mathrm{T}$, $\mathbf{b} = (1, 1, ..., 1)^T$, $\mathbf{I}$ and $\mathbf{B}$ are the identity and all one matrices with appropriate dimensions respectively. Substituting it into (16) gives the outage probability as

$$P_{out} = \mathrm{diag}(\mathbf{A})^\mathrm{T} \cdot (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1} \mathbf{b}, \tag{17}$$

where $\mathrm{diag}(\mathbf{A})$ is a vector consisting of all diagonal elements of $\mathbf{A}$, and A_{ji} is obtained in (5) and (12) for $i = j$ and $i \neq j$ respectively.

V. DELAY AND DIVERSITY PERFORMANCE

This section derives the average packet delay, diversity order and error floor to better reveals the performance of the proposed scheme.

A. Average packet delay

The delay of a packet in the system is the number of time slots for a packet to leave the source node and arrive the destination. Because it takes one time slot to transmit a packet from the source to a relay node, the average packet delay in the system is given by

$$\bar{D} = 1 + \bar{D}_r, \tag{18}$$

where $\bar{D}_r$ is the average delay at the relay nodes. Based on Little's Law [22], we have

$$\bar{D}_r = \frac{1}{\bar{\xi}} \sum_{k=1}^K \bar{q}_k, \tag{19}$$

where $\bar{\xi}$ is the average throughput of the network and $\bar{q}_k$ is the average buffer queuing length at relay R_k.

Because every packet takes two time slots (not necessarily consecutively) to reach the destination, the average data rate (without considering the outage probability) is $1/2$ data packet per time slot. Thus we have $\bar{\xi} = 1/2 \cdot (1 - P_{out})$. On the other hand, $\bar{q}_i$ is obtained by averaging the buffer lengths at R_k over all states $\mathbf{q}_i$ as

$$\bar{q}_k = \sum_{i=1}^{(L+1)^N} \pi_i q_{i,k}. \tag{20}$$

Substituting $\bar{\eta} = 1/2 \cdot (1 - P_{out})$ and (20) into (18), gives the average packet delay in the proposed scheme as

$$\bar{D} = 1 + \frac{2}{1 - P_{out}} \sum_{k=1}^K \sum_{i=1}^{(L+1)^N} \pi_i q_{i,k}. \tag{21}$$

B. Diversity order

The diversity order is defined as

$$d = -\lim_{\bar{\lambda} \to \infty} \frac{\log P_{out}}{\log \bar{\lambda}}. \tag{22}$$

The system's diversity order is determined by the individual diversity order at every state, and the general closed form is difficult (if not impossible) to obtain. Below we derive the diversity order at state $\mathbf{q}_i$ and in the next section we derive the overall system diversity order for optimum target buffer lengths.

The diversity order at $\mathbf{q}_i$ is the contribution from all relay nodes. Specifically, the diversity order contributed from relay R_k consists of 3 cases:

1) Case 1 - Both $S \to R_k$ and $R_k \to D$ links are available at R_k: This corresponds to a '$P(out_m, out_{m'})$' outage term in (5). Using (9) into (22), and from (8) and (10), the diversity order contributed from relay R_k in this case is given by

$$
\begin{aligned}
d_{s \to r_k \to d} &= -\lim_{\bar{\lambda} \to \infty} \frac{\log(P(out_m, out_{m'}))}{\log \bar{\lambda}} \\
&= -\lim_{\bar{\lambda} \to \infty} \frac{\log(\bar{\lambda}^{-2} \cdot P_{\varphi_k} F_2 + \bar{\lambda}^{-1} \cdot (1 - P_{\varphi_k}) F_1)}{\log \bar{\lambda}} \\
&= \begin{cases} 1, & P_{\phi_k} < 1, \\ 2, & P_{\phi_k} = 1 \end{cases}
\end{aligned} \tag{23}
$$

where $F_1 = 1/\pi \int_{r=0}^{r_o} \int_{\theta=0}^{2\pi} d_m^\alpha d_{m'}^\alpha \xi r dr d\theta$, $F_2 = 1/\pi \int_{r=0}^{r_o} \int_{\theta=0}^{2\pi} d_m^\alpha \xi r dr d\theta$. It is interesting to observe that, if R_k and S are in full trust (i.e. $P_{\phi_k} = 1$), although $S \to R_k$ and $R_k \to D$ links have dependent channel gains, they still contribute 2 diversity orders.

2) Case 2 - only $S \to R_k$ link is available at R_k: It corresponds to a '$P(out_m)$' outage term in (5). From (6), the diversity order contributed by R_k is obtained as

$$
\begin{aligned}
d_{s \to r_k} &= -\lim_{\bar{\lambda} \to \infty} \frac{\log P_{\phi_k} P(C_m < \eta) + (1 - P_{\phi_k})}{\log \bar{\lambda}} \\
&= \begin{cases} 0, & P_{\phi_k} < 1, \\ 1, & P_{\phi_k} = 1 \end{cases}
\end{aligned} \tag{24}
$$

3) Case 3 - only $R_k \to D$ link is available at R_k: The diversity order contributed by R_k is given by

$$
d_{r_k \to d} = -\lim_{\bar{\lambda} \to \infty} \frac{\log(P(out_m))}{\log \bar{\lambda}} = -\lim_{\bar{\lambda} \to \infty} \frac{\log(-\bar{\lambda} \cdot F_2)}{\log \bar{\lambda}} = 1. \tag{25}
$$

The above analysis shows that, if a relay node does not have full trust with the source node, the corresponding $S \to R_k$ link does not contribute to the diversity gain even if it is available. This is because when $P_{\phi_k} < 1$, no matter how large the SNR is increased, the link outage probability for $S \to R_k$ never goes to zero.

Applying the above analysis in Case 1-3 gives the diversity order contributed from every node, and adding them together gives the diversity order at state $\mathbf{q}_i$.

C. Error Floor

At state $\mathbf{q}_i$, if there exists at least one available $R_k \to D$ link, its corresponding outage must have $\lim_{\bar{\lambda} \to \infty} P_{out}^{\mathbf{q}_i} = 0$. Only at all zero state, is there no available $R_k \to D$ link. Thus from (16), we have

$$
\lim_{\bar{\lambda} \to \infty} P_{out} = P_\infty(\mathbf{q} = \mathbf{0}) \lim_{\bar{\lambda} \to \infty} P_{out}^{\mathbf{q}=\mathbf{0}} = \beta P_\infty(\mathbf{q} = \mathbf{0}), \tag{26}
$$

where $\beta = \prod_{k=1}^{K}(1 - P_{\psi_k})$ and $P_\infty(\mathbf{q} = \mathbf{0})$ is the probability that the state is all zero when SNR goes to infinity.

It is clear from (26) that if the system contains the all zero state (i.e. $P_\infty(\mathbf{q} = \mathbf{0}) \neq 0$) and no relays has full trust with the source (i.e. $P_{\psi_k} \neq 1$), we have $\lim_{\bar{\lambda} \to \infty} P_{out} \neq 0$ which is the error floor. Correspondingly the diversity order of the overall system is zero. Therefore with trusts, the outage performance depends on not only diversity order but also error floor.

VI. Optimum target length

Carefully choosing target buffer lengths can adjust the buffer states, from which the outage probability and average packet delay are tuned to satisfy the requirements for various applications. In this section, we derive the optimum target buffer lengths for best outage performance and minimum average packet delay when the SNR goes to infinity. For better exposition, we assume that the buffer size $L \geq 3$ in this section. The analysis for $L < 3$ can be similarly obtained.

A. For best outage performance

In order to have best outage performance, either the diversity order shall be as large as possible, or the error floor shall be as low as possible. Thus the target lengths shall at least not to be set to zero, i.e. $\Theta_k \neq 0$. Supposing that there exist M relay nodes having full trusts with the source, there are 2 cases as following:

1) Case 1: $M \neq 0$, i.e. at least one relay node has full trust: For $\Theta_k \neq 0$, the buffer length at every relay can only be either Θ_k or $\Theta_k - 1$. This is because, when the buffer length for relay R_k is at the target length (i.e. $q_{i,k} = \Theta_k$), the $S \to R_k$ link has lower priority for selection than the $R_k \to D$ link, so that the buffer length $q_{i,k}$ can only be decreased by one or remain unchanged at the next time; On the other hand, when $q_{i,k} = \Theta_k - 1$, the corresponding $R_k \to D$ link has lower priority than the $S \to R_k$ links with full trust $P_\phi = 1$, so that $q_{i,k}$ cannot be further decreased.

Therefore as long as the target lengths for all relays are set to $2 \leq \Theta_k \leq L - 1$, all $S \to R_k$ and $R \to D$ links are available at all states and so the maximum diversity order can be achieved. It is then clear that the optimum target buffer length for all relay nodes shall be set to

$$
\Theta_{opt,k} = 2, \quad k = 1, \cdots, K \qquad \exists P_{\phi_k} = 1 \tag{27}
$$

From the diversity order analysis in Section V-B, the diversity orders at all states are the same which is also the diversity order of the overall system as

$$
d = K + M, \quad \exists P_{\phi_k} = 1 \tag{28}
$$

It is interesting from (28) that, when all relays have full trust with the source, the proposed scheme can obtain full diversity of $2K$, which (unlike the max-link scheme) does not require the buffer-sizes go to infinity.

When the optimum target buffer length is set to $\Theta_{opt,k} = 2$ for all k, the buffer queuing lengths can only be 1 and 2. Thus the average buffer length at every node satisfies $1 < \bar{q}_k < 2$. Then from (21), and further noting that $\lim_{\bar{\lambda} \to \infty} P_{out} = 0$, the average packet delay is given by

$$
1 + 2K < \left(\lim_{\bar{\lambda} \to \infty} \bar{D} = 1 + 2 \sum_{k=1}^{K} \bar{Q}_k \right) < 1 + 4K, \tag{29}
$$

where $\Theta_k = 2, \exists P_{\phi_k} = 1$. It is clear from (29) that the average packet delay does not depend on the buffer size, and so it is significantly smaller than that for the max-link scheme ([23]) which is $KL + 1$ when buffer size is long enough. Therefore, the proposed scheme can achieve not only better outage performance but also lower average packet delay than the max-link scheme.

2) Case 2: $M = 0$, i.e. no relay node has full trust: Because no relay has full trust with the source, the buffer queuing lengths at every relay node satisfy $0 \leq q_{i,k} \leq \Theta_k$. This implies that, no matter how we choose the target buffer lengths, the buffers must

consist of the all zero state. Then from the analysis Section V-C, the diversity order is zero. In order to minimize the error floor, from (26), the target buffer length shall be as large as possible to minimize $P_\infty(\mathbf{s} = \mathbf{0})$. Thus the optimum target buffer length is the same as the buffer size which is given by

$$\Theta_{opt,k} = L, \qquad P_{\phi_k} < 1 \text{ for all } k \qquad (30)$$

B. For minimum packet delay

In order to achieve the minimum packet delay, it is clear the target buffer length shall be set to zero for all relay nodes (i.e. $\Theta_k = 0$). Below we derive the diversity order, error floor and average packet delay respectively.

If the target length $\Theta_k = 0$ for all k, the buffer states can only be $\mathbf{0}$ or $\mathbf{0}^{(+1)}$ when the SNR goes to infinity, where $\mathbf{0}^{(+1)}$ is the vector where one of its elements is 1 and all others are 0. This is because when the buffer state is $\mathbf{0}$, either one $S \to R_k$ link is selected that the buffer state becomes $\mathbf{0}^{(+1)}$, or no link can be selected so that the buffer state remains at $\mathbf{0}$. On the other hand, if the buffer state is $\mathbf{0}^{(+1)}$, the $R_k \to D$ link corresponding to relay with buffer length 1 will be selected and the buffer state goes back to $\mathbf{0}$.

Then from the diversity order analysis in Section V-B we have

$$\begin{cases} d = 0, & P_{\phi_k} < 1 \text{ for all } k \\ M \leq d \leq M+1, & \exists P_{\phi_k} = 1 \end{cases} \qquad (31)$$

where $M > 0$ which is the number of relays having full trusts with the source. It is clear from (31) that the diversity order depends on the number of relays with full trust with the source. Particularly, if no relay has full trust, the diversity order is 0. And from (26), the error floor is given by

$$\begin{aligned} \text{error floor} &= \beta P_\infty(\mathbf{s} = \mathbf{0}) \\ &= \frac{\beta}{2-\beta}, \qquad \Theta_k = 0 \text{ and } P_{\phi_k} < 1 \text{ for all } k, \end{aligned} \qquad (32)$$

where $P_\infty(\mathbf{s} = \mathbf{0}) = 1/(2-\beta)$ which is obtained in (35) in Appendix I.

In all cases, the average packet delay is given by

$$\lim_{\bar{\lambda} \to \infty} \bar{D} = 2, \qquad \Theta_k = 0 \text{ for all } k. \qquad (33)$$

The proof is given in Appendix I. It is clear from (33) that setting the target buffer length as $\Theta = 0$ can reach the minimum possible delay when the SNR is high enough.

VII. NUMERICAL SIMULATIONS

In the simulations below, the target transmission rates in all schemes are set to $R = 1$ bps/Hz. There are 3 relay nodes with positions randomly distributed within the circle shown in Fig. 1, where the circle radius is set to $r_o = 50$. The path lose degradation factor is set to $\alpha = 3$. All simulation results are obtained with $1,000,000$ Monte Carlo runs. The buffer size is set to $L = 5$.

We consider two cases in this section. In Case 1, one of the relays has full trust with the source such that the trust levels for the 3 relays are set to $P_{\varphi_1} = 1$, $P_{\varphi_2} = 0.8$ and $P_{\varphi_3} = 0.6$ respectively. Fig. 3 (a) and (b) show the outage probabilities and average packet delays *vs* transmission SNR (P_{tx}/σ_n^2) respectively. For comparison, the results for the non-buffer-aided *max-min* and the existing buffer-aided *max-link* schemes are also shown. The proposed trust-aware scheme is tuned to achieve best outage performance and minimum average packet delay by setting the target buffer length as 2 and 0 respectively. It is clearly shown that
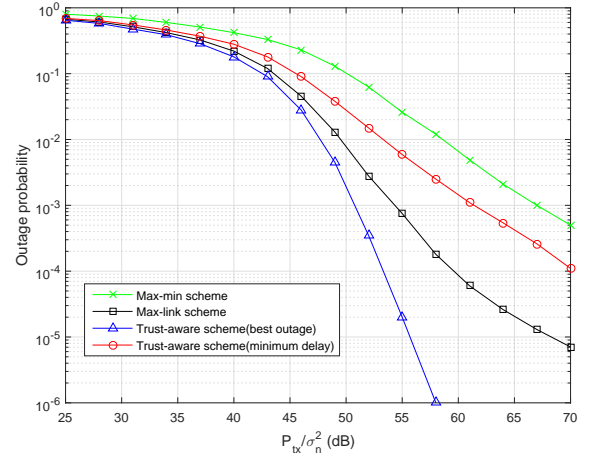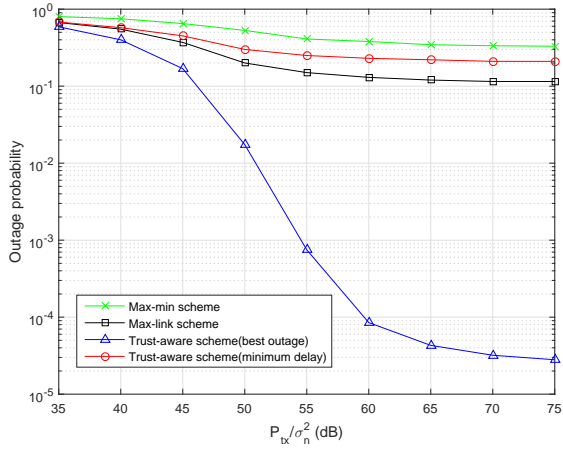

(a) Outage probability
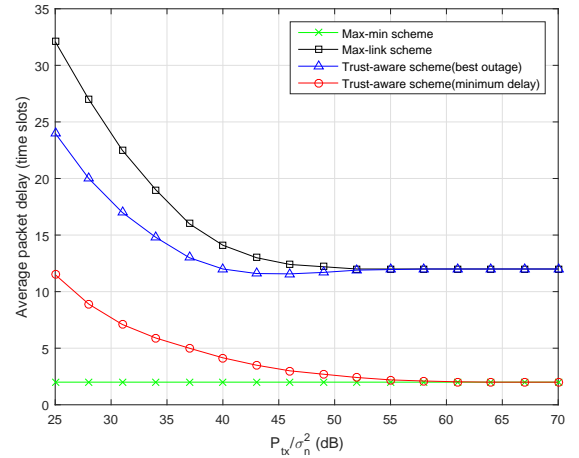
(b) Average delay

Fig. 3. Case 1 - The first relay has full trust with the source, where the trust levels are set as $P_{\varphi_1} = 1$, $P_{\varphi_2} = 0.8$ and $P_{\varphi_3} = 0.6$ respectively. The 'Trust-aware (best outage)' and 'Trust-aware (minimum delay)' curves are for the proposed trust-aware scheme by setting target length as 2 and 0 respectively.
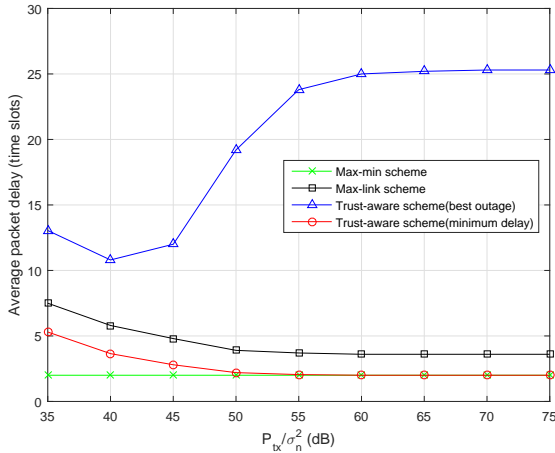
the trust-aware scheme for best outage is superior to the max-link scheme in both outage probability and average packet delay. On the other hand, the trust-aware scheme for minimum delay can achieve the minimum average delay of 2 when the SNR is large enough, but its outage performance is not as good as the max-link scheme.

In Case 2, no relay has full trust with the source, where the trust values are set to $P_{\varphi_1} = 0.4$, $P_{\varphi_2} = 0.3$ and $P_{\varphi_3} = 0.2$. Fig. 4 (a) and (b) show the outage probabilities and average packet delay respectively. As is expected, the error-floors are clearly shown in Fig. 4 (a). Similar to the results in Fig. 3, the proposed trust-aware scheme can be tuned to achieve either best outage performance or minimum packet delay by setting the target buffer length as 5 and 0 respectively. Particularly the outage improvement is even more obvious in Fig. 4 than that in Fig. 3 when the proposed scheme set to achieve best outage performance. This is not surprising as the trust levels in Fig. 4 are poorer than those in Fig. 3, which makes the transmission links between $S \to R_k$ and $S \to D$ be more 'unbalanced'.

Fig. 5 (a) and (b) show how the outage probability and average

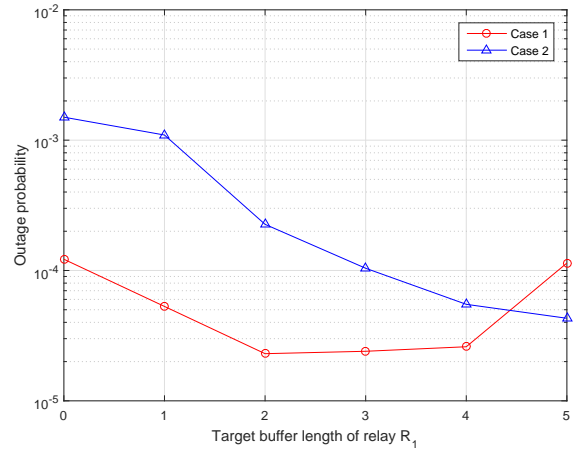(a) Outage probability

(a) Outage probability

(b) Average delay

Fig. 4. Case 2 - no relay has full trust with the source, where $P_{\varphi_1} = 0.4$, $P_{\varphi_2} = 0.3$ and $P_{\varphi_3} = 0.2$. The 'Trust-aware (best outage)' and 'Trust-aware (minimum delay)' curves are for the proposed trust-aware scheme by setting target length as 5 and 0 respectively.

(b) Average delay

Fig. 5. Outage and delay *vs* target buffer length for Relay 1. In **Case 1**: $P_{\phi_1} = 1$, $P_{\phi_2} = 0.8$ and $P_{\phi_3} = 0.6$. In **Case 2**: $P_{\varphi_1} = 0.4$, $P_{\varphi_2} = 0.3$ and $P_{\varphi_3} = 0.2$
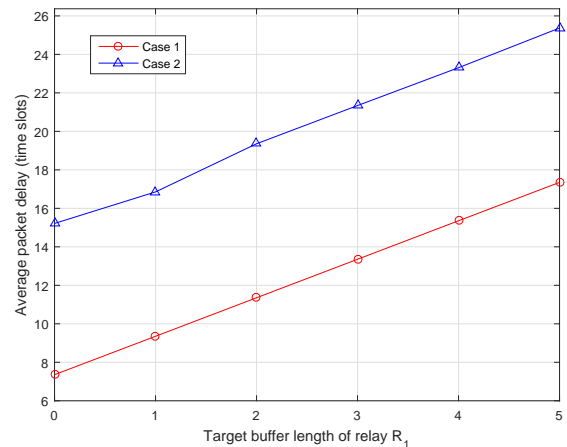
packet delay are affected by the target buffer length, where the SNR-s are fixed at 55 dB and 75 dB, and all other parameters are set as same as those in Fig. 3 and 4, for Case 1 and 2 respectively. In order to observe the influence of the individual target buffer length for every relay node, Relay 1's target buffer length varies from 0 to L, while buffer lengths for other relays are all fixed at 2 and 5 in Case 1 and 2 respectively. It is clearly shown in Fig. 5 (a) and (b) that, in Case 1, the optimum target buffer lengths for best outage performance and minimum delay are 2 and 0 respectively. While in Case 2, the optimum target buffer length for best outage performance and minimum delay is 5 and 0 respectively. These results very well matches our analysis in Section VI.

VIII. CONCLUSIONS

This paper proposed a novel buffer-aided relay selection scheme for trust aware relay networks. By setting appropriate target buffer lengths at relay buffers, the proposed scheme is able to achieve tradeoff between the outage performance and packet delay. Particularly the proposed scheme can achieve better performance in both outage probability and average packet delay than the benchmark max-link buffer-aided scheme. Both the outage probability and

average packet delay have been obtained for the relay network with spatially random relays. We show that, in the trust-aware network, the outage performance depends not only on diversity order but also error floor, which is very different from non trust aware network. The optimum target buffer lengths for best outage performance and minimum average delay have both obtained. The analysis shows that it is more necessary to control the buffer queuing lengths in the trust-aware network than in the non-trust-aware network, because the trusts make the $S \to R_k$ and $R_k \to D$ transmissions more unbalanced.

APPENDIX I

If the target buffer lengths are set to $\Theta_k = 0$ for all k, the buffer states can only be $\mathbf{0}$ or $\mathbf{0}^{(+1)}$ when the SNR goes to infinity. We can then re-group the buffer states and form a new Markov chain as is shown in Fig. 6.

The state transition matrix for Markov chain shown in Fig. 6 is given by

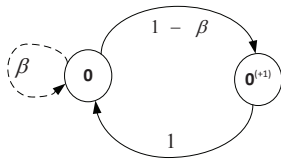$$\mathbf{A} = \begin{pmatrix} \beta & 1 \\ 1-\beta & 0 \end{pmatrix} \tag{34}$$

Fig. 6. Buffer state transition when the target buffer lengths are set to $\Theta_k = 0$ for all k.

Thus we have

$$\begin{pmatrix} P_\infty(\mathbf{s} = \mathbf{0}) \\ P_\infty(\mathbf{s} = \mathbf{0}^{(+1)}) \end{pmatrix} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\mathbf{b} = \begin{pmatrix} \frac{1}{2-\beta} \\ \frac{1-\beta}{2-\beta} \end{pmatrix} \quad (35)$$

where $P_\infty(\mathbf{s} = \mathbf{0})$ and $P_\infty(\mathbf{s} = \mathbf{0}^{(+1)})$ are the probabilities for buffer state at $\mathbf{0}$ and $\mathbf{0}^{(+1)}$ when the SNR goes to infinity respectively. Then we have

$$\lim_{\bar{\lambda} \to \infty} \sum_{k=1}^{K} \bar{q}_k = 1 \times P_\infty(\mathbf{s} = \mathbf{0}^{(+1)}) = \frac{1-\beta}{2-\beta} \quad (36)$$

And from (26) the outage probability is given by

$$\lim_{\bar{\lambda} \to \infty} P_{out} = \beta \cdot P_\infty(\mathbf{s} = \mathbf{0}) = \frac{\beta}{2-\beta}, \quad (37)$$

Substituting (36) and (37) into (21) gives the average packet delay as

$$\lim_{\bar{\lambda} \to \infty} \bar{D} = \lim_{\bar{\lambda} \to \infty} \left(1 + \frac{2}{2-P_{out}} \sum_{k=1}^{K} \bar{q}_k\right) = 2, \quad \Theta_k = 0 \text{ for all } k. \quad (38)$$

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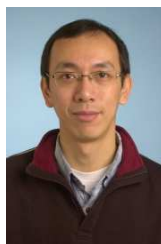
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