QUEUE LENGTH-BASED OPPORTUNISTIC RELAY SELECTION FOR COOPERATIVE WIRELESS NETWORKS

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ABSTRACT

Cooperative communications have been considered as a powerful technique for enhancing network reliability by increasing the successful packet transmission probability. In this paper, we propose an opportunistic cooperative scheme for single-hop wireless networks that exploits the signal-to-noise ratio and the remaining queue length at each potential relay to choose the best relay for the source-destination link. The best relay (or the winner node) is the relay node that expires their timer first and becomes the helper for the direct link. The proposed method is based on the local channel measurement and requires no topology information. The collision probability of the proposed relay selection scheme is analyzed with the combination between continuous and discrete-time random variables. Simulation results are conducted to evaluate the ability of the proposed scheme in improving the network performance in terms of the packet delivery ratio. The proposed cooperative scheme leads to single-hop wireless network applications such as cellular networks and 802.11-based networks.

Keywords: *relay selection; cooperative communications; random access; queue length; packet delivery ratio.*

1. INTRODUCTION

Cooperative diversity is a potential solution to enhance the reliability and performance of wireless networks by increasing the probability of success for packet transmission [1]-[6]. In [7], El–Sherif and Liu presented a novel cooperative scheme for random access networks that is modeled using Markov chains and queueing analysis. However, the cooperation is implemented through a predefined relay node, without the relay assignment process. Alonso-Zarate et al. presented a MAC protocol called PRCSMA [8] to coordinate the retransmissions of the relays based on ARQ. However, these schemes do not take the channel condition and interference caused by the relay assignment process into account. In [9], Jiang et al. proposed a robust cooperative scheme based on space-time coding to deal with the outdated channel state information where a predefined number of relays, instead of a single relay in opportunistic relay selection schemes, are opportunistically selected from some K cooperating relays. In [10], Eltayeb et al. proposed a compressive sensing based relay selection algorithm that reduces the feedback overhead of relay networks under the assumption of noisy feedback channels. In [11], a max - link relay selection scheme was incorporated the instantaneous strength of the wireless channel and the status of the finite relay buffers to provide diversity gains for applications without latency constraints. However, the selection scheme in [11] simply considered the relay buffers to decide the available links that participate in the relay selection decision.

Laneman et al. [12] categorized two relay strategies called selective relaying (SR) and incremental relaying (IR). For the SR scheme, if the channel response is lower than a certain threshold, the source will retransmit the packet to the destination. Otherwise, the relay forwards the packet toward the destination, instead [3]. 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, the IR exploits the limited feedback from the destination to improve the efficiency in using the degree of freedom of the channel capacity. 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 can be decoded incorrectly, which causes more errors at the destination.

In this paper, we propose an adaptive strategy to overcome the drawbacks of the foregoing two schemes and harness the advantages of cooperative diversity to improve network reliability and utilization efficiency. This study focuses on the system-level performance evaluation to enhance the network performance with the following contributions: (1) the proposed cooperative scheme improves the network performance in terms of the packet delivery ratio; (2) the relay assignment is based on the CSI and the current queue length of the transmitting buffer of each relay so that the most available path for information relaying is chosen; and (3) probabilistic analysis regarding the failure of the best relay selection is provided. The proposed scheme leads to applications of single-hop wireless networks such as cellular networks and 802.11-based networks.

2. SYSTEM MODEL

We make the following assumptions: (1) the fading channels between nodes are flat in frequency and quasi-static Rayleigh fading; (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 the random access.

If P_i is the received signal power at receiver j from the source i, P_k denotes the interference power of other signals at j from its surrounding nodes, and N is the noise power (all in Watts).

Assuming that all nodes use an average transmitted power P similarly under the impact of a flat fading channel, the capacity *C(i, j)* [bits/second] of link *i-j* calculated at receiver j with an infinite bandwidth W [Hz] and power spectral density $N_0/2$ [W/Hz] related to the SINR by Shannon’s theorem is

$$C(i,j) = Wlog_2(+\frac{P|h_{i,j}|^2 d_{i,j}^{-\alpha}}{N_0W+\sum_{k\neq i}P|h_{k,j}|^2 d_{k,j}^{-\alpha}}) \quad (1)$$

where $h_{i,j}$, $h_{k,j}$, and $d_{i,j}$, $d_{k,j}$ denote the channel gain and the distance between i, k, and j, respectively. $h_{i,j}$ and $h_{k,j}$ represent the small-scale fading from the transmitter to the receiver, whereas $d_{i,j}^{-\alpha}$ and $d_{k,j}^{-\alpha}$ approximate the signal path loss through the environment. The calculated capacity is compared with the required rate $R_{req.}$

3. DESCRIPTION OF THE COOPERATIVE SCHEME

3.1 Source Transmission

The source node denoted by s sends the data packet toward its surrounding nodes. All neighbors receive and estimate the SINR with respect to the incoming packet.

3.2 Relay and Destination Checking

All neighbors, including relays r and destination d, receive the packet and calculate the respective channel capacity. Once this value satisfies the required rate, an acknowledgment (ACK) frame is broadcasted by the destination to all surrounding nodes with the ID of the respective data packet. Then, the potential relays recognize that the packet has been received at the destination successfully, and they remove the packet from their buffer because more transmissions from the relays are not necessary. Otherwise, the destination sends a NACK and defers to the next phase.

3.3 Relaying Contention

The source and destination maintain the set of their neighbors, given by 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 are joined in the relaying selection to reduce the contention area. The source s also can retransmit the packet if it wins the competition with other relays. If the calculated channel capacity satisfies the required rate, the packet overheard from the source will be stored in reserve for the relay selection phase. 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. (2):

$$t = \frac{k}{\rho_i (L - q_i)} = \frac{k}{\rho_i \overline{q_i}} \qquad (2)$$

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.

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 seconds.

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. However, for the special case that some relays are in hidden state from 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 assignment: if a node has more packets in the queue, it has lower priority to become a relay node for another source-destination pair.

3.4 Destination Combining

At the destination, if the packet from the source is received successfully, an ACK packet is sent to confirm the successful reception. Otherwise, an NACK packet is broadcast, and the relay selection phase starts as in the second step. The destination also stores the packet for a further combining process. Once the incoming packet is received successfully, it is forwarded to higher layer for further processing. However, in the worst case, when all retransmission attempts have failed, the destination will use the maximal ratio combining technique [12],[13] to recover the original packet from the previous replicas.

4. PROBABILISTIC ANALYSIS OF THE PROPOSED RELAY ASSIGNMENT SCHEME

The failure of the relay assignment scheme occurs since there are more than one relay that become 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.

4.1 Cases of Failure

Based on the operation of the proposed relay assignment scheme, we consider two cases of failure as shown in Fig.1: (1) all relay candidates N can listen to each other and (2) some relays in set N are hidden from each other. It is noted that the cooperative scheme occurs 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 switching time from receive-to-transmit mode (Eq. 3). 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. 4). 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.

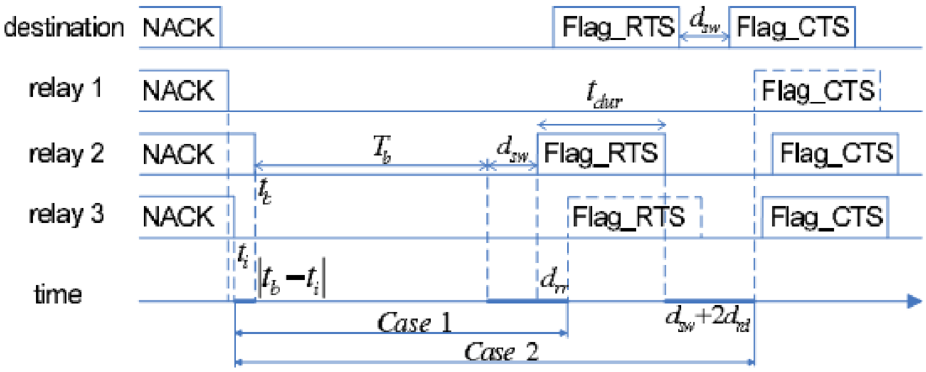

Figure 1. *Illustration for failure probability*

$$c = |t_b - t_i|_{max} + d_{rr-max} + d_{sw} \tag{3}$$

$$= |t_b - t_i|_{max} + d_{rr-max} + 2d_{sw} + t_{dur} + 2d_{rd-max} \tag{4}$$

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:

$$Pr(collision) = Pr(any\ T_i - T_b < c |\ i \neq b, i\ N) \tag{5}$$

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

$$Pr(any\ T_i - T_b < c |\ i \neq\ b, i\ N\ ) \equiv \Pr(U_2 < U_1 + \mathrm{c}) \tag{6}$$

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*. Eq. 6 can thus be written

$$\Pr(U_2 < U_1 + \mathrm{c}) = \Pr\left(\frac{1}{|h_{k,j}|^2 \overline{q_2}} < \frac{1}{|h_{1,j}|^2 \overline{q_1}} + \frac{c}{k}\right) \tag{7}$$

Then, the probability of failure can be calculated by Lemma1 in [8]

$$\Pr(U_2 < U_1 + \mathrm{c}) = 1 - I_c \tag{8}$$

$$\mathrm{I}_c = (N-1) \int_c^{\infty} f(u)[1 - F(u)]^{N-2} F(u - c) du \tag{9}$$

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.

4.2 Probabilistic Analysis

To calculate the probability in Eq. 9, we need to calculate the probabilistic functions of the timer T_i. The CDF and PDF of each T_i are respectively given by:

$$\mathrm{F(t)} = \Pr[T_i \le t] = 1 - \Pr[T_i > t] = 1 - CDF_{|h_i|^2\bar{q}}\left(\frac{k}{t}\right) \tag{10}$$

$$\mathrm{f(t)} = \frac{d}{dt}F(t) = \frac{k}{t^2}PDF_{|h_i|^2\bar{q}}\left(\frac{k}{t}\right) \tag{11}$$

where $CDF_{|h_i|^2\bar{q}}$ and $PDF_{|h_i|^2\bar{q}}$ 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.

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 λ > 0 are given by [14]

$$F_X(x) = 1 - e^{-\lambda x}(x \ge 0) \tag{12}$$

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

2) **Queue Model:** For a simplicity, we assume that node queues can be modeled as M/G/1 queues which receive packets based on a Poisson arrival process with arrival rate λ_s packets/sec and service rate µs depending on the channel access mechanism [7]. The thorough analysis of the 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 detailed queueing analysis will remain an important part of future work. We follow a simple approximation for the M/G/1 queue length distribution in [15] 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

$$P[\bar{N} = k] = P[N = L - k] \approx U_0\alpha^{L-k-1}(1-\alpha) \tag{14}$$

for $k = 0, 1, 2, \dots, L-1$

and $P[\bar{N} = k] = 1 - U_0$

3) **Distribution of the timer function:** We obtain the joint CDF and PDF of the product of the above random distributions $|h_i|^2\bar{q}$

$$\mathrm{F(t)} = 1 - \Big[U_0\alpha^{L-1}(1-\alpha) + \textstyle\sum_{y=1}^{L-1} U_0\alpha^{L-y-1}(1-\alpha)\left(1-e^{-\lambda\frac{k}{yt}}\right) + (1-U_0)\left(1-e^{-\lambda\frac{k}{Lt}}\right)\Big] \tag{15}$$

$$\mathrm{f(t)} = \frac{\mathrm{k}}{\mathrm{t}^2}\left[\sum_{y=1}^{L-1}\frac{1}{y}U_0\alpha^{L-y-1}(1-\alpha)\lambda e^{-\lambda\frac{k}{yt}} + (1-U_0)\lambda e^{-\lambda\frac{k}{Lt}}\right] \tag{16}$$

The probability of failure is now calculated by substituting the above two equations into Eq. 9. The probability of collision is calculated with the average value of any channel coefficient $\lambda = E\left[|h_{i,j}|^2\right] = 1$ and $N = 7$ nodes. Besides, other parameters such as U_0, L are set to 0.85 and 100, respectively.

4.3 Results

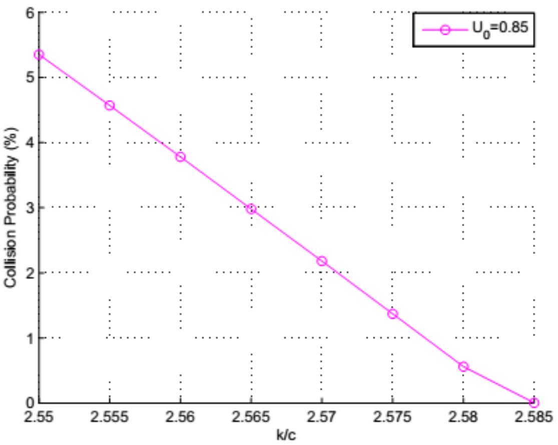

Figure 2. *The probability of collision versus various values of k/c in the case N=7 and U_0 = 0.85*

The probability of collision is calculated with the average value of any channel coefficient $\lambda = E\left[\left|h_{i,j}\right|^2\right] = 1$ and $N = 7$ nodes. Besides, other parameters such as U_0, L are set to 0.85 and 100, respectively. It is seen in Eq. 7 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. 9, the collision probability is a function of *k/c*. The results are plotted in Fig. 2 for various values of *k/c* with the server utilization U_0= 0.85. Assume that the distance between network nodes is less than 100 m. Whereas typical switching time should be less than 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 less than 1% according to a range of the server utilization U_0.

Table 1. *List of k according to a range of U_0*

U_0	0.6	0.65	0.7	0.8	0.85	0.9
k/c	6.91	6.1	5.29	3.49	2.58	1.93
k ($x10^{-6}$)	138	122	106	70	52	39
Prob. ($x10^{-3}$)	5.1	5.6	7.6	7.3	5.6	4.3

5 PERFORMANCE EVALUATION

The proposed scheme is evaluated by simulation using OPNET Modeler 16.0 and compared with two schemes: (1) direct transmission (without cooperation) and (2) the best relay scheme based on only channel estimation [3]. We adapt the standard IEEE 802.11 MAC for the proposed scheme with some modifications to the physical layer. Whereas the relay assignment is executed at the MAC layer. A group of 7 nodes and 1 sink are deployed within a coverage range of 100 m × 100 m. Each node generates traffic with a packet length of 500 bytes according to an exponential inter-arrival time. The transmission range is set to 100 m, and the data rate is 11 Mbps. We compared the performance of the three schemes in terms of the packet delivery ratio (PDR). Each simulation result is executed through 5 simulation rounds and a confidence interval of 90%.

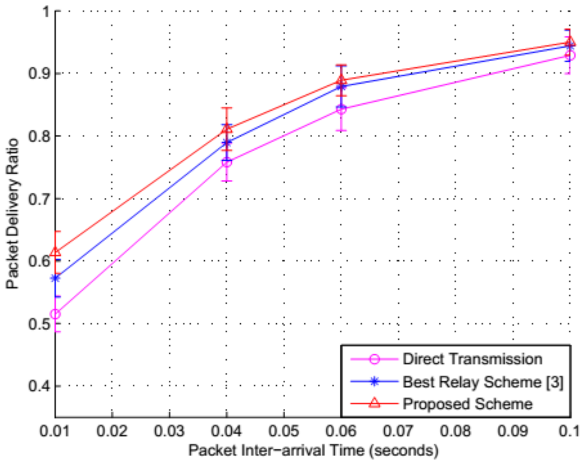

Figure 3. *The PDR with respect to packet inter-arrival times*

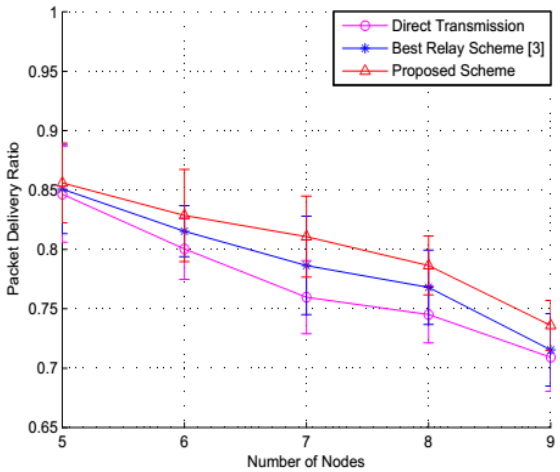

Figure 4. *The PDR with respect to node density*

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. Fig. 3 and Fig. 4 show the PDR versus various packet inter-arrival times and the number of network nodes, respectively. It is seen that in case of low traffic (i.e., a large value of the packet inter-arrival times) or small number of network nodes, the performance of the three schemes is almost same because in such cases the impact of packet collision and interference is small which leads to more reliable for packet transmission. However, an increase in network traffic, the PDR is reduced in all three schemes. Similarly, an increase in the number of network nodes also reduces the number of receiving packets at the sink. This is because the higher traffic produces more collisions and interference for the surrounding nodes, which may 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. 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 in the sink. Moreover, an advantage of the proposed scheme in comparison with the best relay scheme [3] is that our scheme reduces unnecessary transmission from the best relay which may cause more collision for other transmission if the sink successfully decodes the packets from the source for the first time.

6 CONCLUSIONS

In this paper, we presented an opportunistic relay assignment scheme for single-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 reduce the collision probability between feedback and data packets via more effective scheduling strategies.

REFERENCES

[1] K. J. Ray Liu, Ahmed K. Sadek, Weifeng Su, Andres Kwasinski, “Cooperative Communications and Networking”, Cambridge University Press, Dec 2008.

[2] Abdulhadi, S.; Jaseemuddin, M. & Anpalagan, A. A Survey of Distributed Relay Selection Schemes in Cooperative Wireless Ad hoc Networks Wireless Personal Communications, 2012, 63, 917-935.

[3] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, A simple cooperative diversity method based on network path selection, *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 659 – 672, march 2006.

[4] Liang, X., Chen, M., Balasingham, I. and Leung, V. C. (2013), Cooperative communications with relay selection for wireless networks: design issues and applications. Wirel. Commun. Mob. Comput., 13: 745-759.

[5] F. Gomez-Cuba, R. Asorey-Cacheda and F. J. Gonzalez-Castano, "A Survey on Cooperative Diversity for Wireless Networks," in IEEE Communications Surveys & Tutorials, vol. 14, no. 3, pp. 822-835, Third Quarter 2012.

[6] Y.-W. Hong, W.-J. Huang, F.-H. Chiu, and C.-C. Kuo, Cooperative communications in resource-constrained wireless networks, *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 47 –57, may 2007.

[7] A. El-Sherif and K. Liu, Cooperation in random access networks: Protocol design and performance analysis, *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 9, pp. 1694 –1702, october 2012.

[8] J. Alonso-Zarate, E. Kartsakli, C. Verikoukis, and L. Alonso, Persistent RCSMA: A MAC protocol for a distributed cooperative ARQ scheme in wireless networks, *EURASIP Journal on Advances in Signal Processing*, vol. 2008, no. 1, p. 817401, 2008.

[9] W. Jiang, T. Kaiser and A. J. H. Vinck, "A Robust Opportunistic Relaying Strategy for Co-Operative Wireless Communications," in IEEE Transactions on Wireless Communications, vol. 15, no. 4, pp. 2642-2655, April 2016.

[10] M. E. Eltayeb, K. Elkhalil, H. R. Bahrami and T. Y. Al-Naffouri, "Opportunistic Relay Selection With Limited Feedback," in IEEE Transactions on Communications, vol. 63, no. 8, pp. 2885-2898, Aug. 2015.

[11] I. Krikidis, T. Charalambous, and J. Thompson, Buffer-aided relay selection for cooperative diversity systems without delay constraints, *IEEE Transactions on Wireless Communications*, vol. 11, no. 5, pp. 1957–1967, May 2012.

[12] J. Laneman, D. Tse, and G. Wornell, Cooperative diversity in wireless networks: Efficient protocols and outage behavior, *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062 – 3080, December 2004.

[13] D. Brennan, Linear diversity combining techniques, *Proceedings of the IEEE*, vol. 91, no. 2, pp. 331 – 356, february 2003.

[14] O. C. Ibe, Fundamentals of Applied Probability and Random Processes, *Elsevier Academic Press*, 2005.

[15] D. S. Myers and M. K. Vernon, Estimating queue length distributions for queues with random arrivals, *SIGMETRICS Perform. Eval. Rev.*, vol. 40, no. 3, pp. 77–79, Jan. 2012.

[16] B. G. Lee and S. Choi, Broadband Wireless Access & Local Networks: Mobile WiMAX and Wi-Fi, *Artech House Publishers*, 2008.

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