

## Research Article

# An Analytical Approach to Opportunistic Transmission under Rayleigh Fading Channels

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In cognitive radio sensor networks, the routing methods including multiple relays have been extensively studied to achieve higher throughput and lower end-to-end delay. As one of innovative approaches, the opportunistic routing scheme was proposed. In this paper, the effectiveness of the opportunistic transmission in terms of reliability and delay of transmission is verified with an analytical way. For the analysis, we establish the probabilistic model with respect to distance and the number of relay nodes under the Rayleigh fading channels including path loss effects. Under this model, we develop a generic Markov chain model to obtain the analytical results and verify the effectiveness of the statistical analysis. The results show that an opportunistic transmission approach is better than traditional multihop transmissions in terms of successful data delivery with fewer transmissions. Consequently, it can provide an energy efficient transmission mechanism for cognitive radio sensor networks.

## 1. Introduction

Reliable data delivery with the fewest hops, keeping end-to-end delay and overhead minimized, is always a prime focus in cognitive radio sensor networks research that results in increased throughput. Moreover, the effectiveness of cognitive radio sensor networks is dependent on the development of the effective and energy efficient protocols. The key idea in opportunistic routing is to exploit the probability of reaching the farthest node in one transmission. If we can transmit a packet successfully, directly or with the fewest hops, even with low probability, we can drastically improve throughput and reduce end-to-end delay. The key challenge of this research is to analyze opportunistic transmission (OT) statistically and show that it is better in terms of successful transmissions and requires fewer transmissions, compared to traditional multihop transmissions, under the assumption that end-to-end distance is known.

The cognitive radio sensor networks are powered by finite energy resources. Recent trends in cognitive radio sensor networks [1] and introduction of wireless multimedia sensor

networks [2] highlight the importance of energy consumption. Therefore, more research is inclined to increase the cognitive radio sensor network lifetime [3]. Transmission of packets in multihop wireless networks poses a great challenge because of unreliability and inherent interference of wireless links [4]. Wireless multihop networks [5–7] encompass mobile or stationary stations interconnected via an ad hoc multihop path. Each node operates not only as a host but also as a router and forwards packets on behalf of other nodes that may not be within direct radio range of the destinations. Among recent advances, opportunistic routing has appeared as an appealing multihop routing method, which gives high throughput in dynamic wireless environments.

Opportunistic routing (OR) [8–16] takes advantage of the spatial diversity and broadcast nature of wireless networks to combat time-varying links by involving multiple neighboring nodes, also known as forwarding candidates, for each packet transmission [17]. Adopting a different philosophy in route selection, OT chooses the closest node to the destination to forward a packet out of the set of nodes that actually received previous packets. This results in high expected progress per

transmission. The flexibility of OT enables agile adaptation in fast-changing wireless environments, which are particularly suitable for serving up high-rate and delay-sensitive interactive traffic [18]. Extremely opportunistic routing (ExOR) integrates routing and medium access control (MAC) protocols. It improves throughput by selecting long-range, but lossy, links. It is designed for batch forwarding. The source node includes the list of forwarders in a packet, based on expected transmission distance from the destination. All packets are broadcast. Each packet contains a BITMAP option, which marks the successfully received packet by the receiver or higher priority nodes. However, this protocol reduces spatial reuse as it is globally synchronized, and there are duplicate transmissions as well.

Opportunistic any-path forwarding (OAPF) [19] overcomes the problem of ExOR choosing low-quality routes. It introduces an expected path-count metric. This approach recursively calculates the near optimal forwarder set at each forwarder. However, this approach incurs high computational overhead. MAC-independent opportunistic routing and encoding (MORE) [20] integrates a network coding OR to enhance ExOR. The core idea is to avoid any duplication of data. It uses the concept of innovative packets to decide whether a received packet contains new information or not. Simulation results show improvement in the total number of transmissions compared to ExOR. Opportunistic routing in dynamic ad hoc networks (OPRAH) [21] builds a threaded multipath set between source and destination. It allows intermediate nodes to have more paths back to the receiver and destination. However, duplicate packet reception is an associated drawback of this protocol.

Resilient and opportunistic mesh routing (ROMER) [22] builds the mesh route for every packet. It assumes there is an existing technique to find the minimum cost from each mesh router to the gateway. When a packet is sent from a mesh router to the gateway, the source mesh router needs to set a credit cost. The overall cost to deliver the packet is the minimum cost plus the credit cost to reach the gateway. The probability that each intermediate router can forward a packet depends on the quality of the link to the parent router. The best-link-quality intermediate node forwards the packet with a probability of 1. The other nodes send the packets with the current rate of the considered link divided by the current rate of the best link. However, the disadvantage of this protocol is that it has to rely on an existing scheme to find the minimum cost from each mesh router to the gateway. The directed transmission routing protocol (DTRP) [23] is a variant of ROMER. It adjusts the probability at a forwarder in a different way. If a node is sitting on the shortest path to the destination, it forwards each packet with a probability of 1. Otherwise, the probability is dependent on the extra distance to reach the destination. The longer the distance, the smaller the probability. Geographic random forwarding (GeRaF) [16] selects the forwarding nodes using location information. Nodes closer to the destination have a higher priority. It adopts hop-by-hop forwarder selection. The disadvantage of this protocol is the cost to acquire the location information. Coding-aware opportunistic routing (CORE) [24] is an integration of confined interflow network

coding and OR. It enables a node to forward a packet to the next hop that leads to the most coding changes. This iterative forwarder-by-forwarder mechanism significantly improves coding gain with a slightly increased protocol overhead.

Cooperative opportunistic routing in mobile ad hoc networks (CORMAN) [25] is a network layer solution to opportunistic data transfer in mobile ad hoc networks. This scheme broadens the applicability of ExOR to mobile multihop wireless networks without relying on external sources. Moreover, it incurs smaller overhead than ExOR by including shorter forwarder lists in data packets. To reduce the overhead in route calculation, they developed proactive source routing [26], which introduced a large-scale live update to increase throughput and decrease delay from forwarder list adaptation. This provides robustness against link-quality variation using small-scale retransmission. Simulation results show that drastic improvement in packet delivery ratio and average delay is achieved, compared to ad hoc on-demand distance vector.

This paper contributes to a new statistical analytical model for studying traditional multihop and OT. The model shows improvement in throughput and fewer transmissions to successfully deliver packets to their destination. Although many analyses have been proposed, this work is unique because we consider cases where the distance is known. Moreover, we develop an innovative generic Markov chain model of our proposed method, which can be applied to other OT scenarios. As far as we know, this is the first method that statistically formulates and shows stability in our proposed OT. We consider all possible probabilities for successful data transmission from source to destination. Using the proposed model, we compare opportunistic transmission with conventional multihop transmission, which determines the most reliable available multihop path. Evaluation results demonstrate that the OT outperforms the best traditional multihop transmission in successful delivery, number of transmissions, transmission power, number of intermediate nodes, and delay.

The rest of the paper is structured as follows. Section 2 explains the system model. Section 3 presents our proposed analytical model, comparing opportunistic transmission with traditional multihop transmission. Section 4 demonstrates the evaluation results based on the proposed statistical analytical model. Finally, Section 5 provides the conclusion and discusses future work.

## 2. System Model

The system consists of sender node  $S$  and receiver node  $R$ . The sender and receiver are at distance  $d$  from each other. In the literature, there are many geographical routing protocols in which nodes know their location. The distance can be calculated using the geometric coordinates and position of all the sensors [27]. Hence, we assume that  $d$  is known. This is a mild and reasonable assumption. We keep the distance fixed, and all the intermediate nodes are at an equal distance from each other. Every intermediate node can relay the packet to nodes within the communication range of it. Let signal  $a$

be transmitted from given sender node  $S$  to receiver  $R$  in a Rayleigh fading channel. The probability density function of received power can be written as

$$f(a) = \frac{1}{P_r} e^{-a/P_r}, \quad (1)$$

where  $P_r$  is the average received power of the signal. Assume that the mean power level falls off according to the power of the range  $P_T/d^\alpha$ .  $P_T$  is the product of transmitted signal power, transmitter and receiver antenna gains, and system loss.  $\alpha$  is a path loss exponent.  $P_T$  is set to 1 for simplicity. In case of static node distribution,  $P_r$  is a constant.

For a given transmission rate  $R_t$ , provided signal-to-noise ratio, the required received power at the receiver to decode a packet successfully is given by

$$R_t = \log \left( 1 + \frac{P_{rt}}{N_0} \right), \quad (2)$$

where the minimum required received power for successfully decoding a packet is given by

$$P_{rt} = N_0 (2^{R_t} - 1). \quad (3)$$

Therefore, successful transmission probability is obtained as follows:

$$\begin{aligned} P_s &= \int_{P_{rt}}^{\infty} \frac{d^\alpha}{P_t} e^{-rd^\alpha/P_t} dr, \\ P_s &= \int_{P_{rt}}^{\infty} \frac{d^\alpha}{P_t} e^{-rd^\alpha/P_t} dr = \frac{d^\alpha}{P_t} \left[ -\frac{P_t}{d^\alpha} e^{-rd^\alpha/P_t} \right]_{P_{rt}}^{\infty} \\ &= (e^{-d^\alpha P_{rt}/P_t}) = \frac{1}{e^{d^\alpha P_{rt}/P_t}}. \end{aligned} \quad (4)$$

### 3. Multihop Transmission

In the multihop scenario, the probability of success can be written as

$$P_s = P_{s_{st}} + P_{s_{sr}}. \quad (5)$$

$P_s$  is the probability of successful transmission from source to destination.  $P_{s_{si}}$  is the probability of successful transmission from sender to intermediate node, and  $P_{s_{ir}}$  is the probability of successful transmission from intermediate node to receiver. The total distance is fixed, and intermediate nodes are equidistant. Therefore, the probability of success will be

$$P_s = (e^{-(d/2)^\alpha P_{rt}/P_t}) (e^{-(d/2)^\alpha P_{rt}/P_t}). \quad (6)$$

$P_s$  for  $n$  nodes is

$$P_s = (e^{-n((d/(n-1))^\alpha P_{rt}/P_t)}). \quad (7)$$

Figure 1 describes the traditional multihop transmission, where  $i$  represents the intermediate nodes.

**3.1. Opportunistic Multihop Transmission.** In OT, the sender transmits the packet with a list of possible forwarders and priorities. The destination has the highest priority, a node that is nearest to the destination has the second highest priority, and so on. All the intermediate nodes can act as a relay and can forward the packet directly to the destination if it is in range; otherwise, the packet goes to the next highest priority node. All the intermediate nodes will keep a copy of overheard packets.

If the highest priority node successfully delivers packets to the destination, then the other nodes will discard the packet. Otherwise, the next highest priority node will try to deliver the packet to the destination. The cumulative success probability is the “success probability of the highest priority node and success probability of the next highest priority node, with the product of failure probability of highest priority nodes with respect to this node.” In case of failure of all possible cases of the OT, the last case is a multihop, and success probability is 1. The receiver will send acknowledgement after successful delivery of the packet with a success probability of 1.

If the number of nodes is 2, then the equation remains the same as in the direct case:

$$P_s = \begin{cases} (e^{-d^\alpha P_{rt}/P_t}), & \text{if } n = 2 \\ (e^{-d^\alpha P_{rt}/P_t}) + (e^{-(d/2)^\alpha P_{rt}/P_t}) (e^{-(d/2)^\alpha P_{rt}/P_t}) (1 - e^{-d^\alpha P_{rt}/P_t}), & \text{if } n = 3 \\ \sum_{i=2}^{n-1} e^{-((n-i)d/(n-1))^\alpha ((i-1)d/(n-1))^\alpha} \prod_{j=2}^i (1 - e^{-((n-j+1)d/(n-1))^\alpha}) + e^{-((d/(n-1))^\alpha)^{n-1} (1 - e^{-d^\alpha})} \prod_{k=0}^{n-3} (1 - e^{-(n-k-2)d/(n-1)})^2 & \text{if } n > 3 \end{cases} \quad (8)$$

With 3 nodes, the total number of hops is 2. The total probability of success is the sum of the probability from source  $S$  to destination  $R$  and the probability from intermediate relay node  $i$  to destination  $R$ , with the product

of failure probability of direct transmission from source to destination.

If the number of nodes is more than 3, this equation shows the overall probability of success for  $n$  nodes, which is

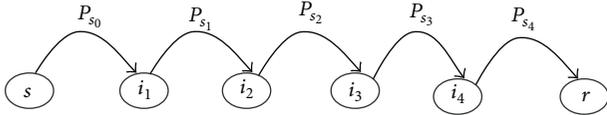


FIGURE 1: Traditional multihop transmission.

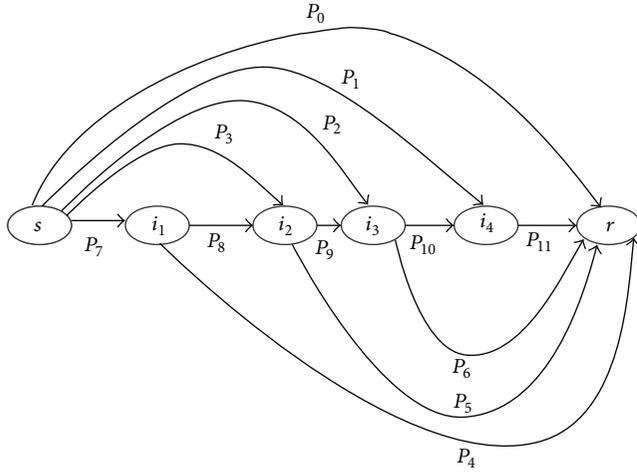


FIGURE 2: Opportunistic transmission.

the recursive summation of all success probabilities with failure probabilities of all the higher priority nodes with respect to that node, up to  $n$  nodes.

Figure 2 depicts the probability of success of all possible routes to the receiver.

**3.2. Expected Number of Transmissions.** The expected number of transmissions (ETX) [28] can be calculated as

$$\text{ETX} = \frac{1}{P_s}. \quad (9)$$

ETX is inversely proportional to the probability of success  $P_s$ .

**3.3. Markov Chain Model for Opportunistic Transmission.**  $X_n$  is the state of a given packet at time  $n$ . In the considered problem, state means the node where the current packet is located. The state transition diagram is shown in Figure 3. The transition  $a_{ij}$  from current state  $i$  to next state  $j$  is

$$a_{ij} = P_r(X_{n+1} = j | X_n = i). \quad (10)$$

If  $m_{j,j}$  is the expected number of transitions until the Markov chain, starting in state  $j$ , returns to that state, then

$$\pi_j = \frac{1}{m_{j,j}}. \quad (11)$$

We are interested in  $m_{j,j}$ . To calculate  $m_{1,1}$  transitions from state 1 till we return to state 1, we have

$$\begin{aligned} m_{1,1} &= m_{1,N} + 1, \\ m_{1,N} &= m_{1,1} - 1. \end{aligned} \quad (12)$$

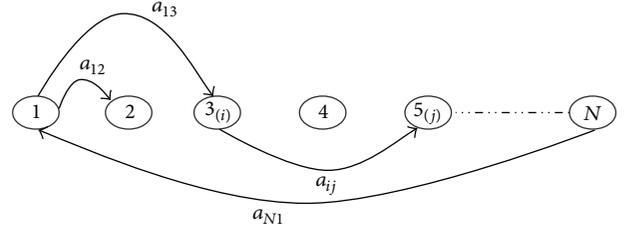


FIGURE 3: State diagram for opportunistic transmission.

The generic state transition matrix is

$$p = \begin{bmatrix} 0 & a_{12} & a_{13} & \cdots & a_{1N} \\ 0 & 0 & a_{23} & \cdots & a_{2N} \\ \vdots & \ddots & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & a_{(n-1)N} \\ a_{N1} & & & & 0 \end{bmatrix}, \quad (13)$$

$$\pi = (\pi_1 \pi_2 \pi_3 \cdots \pi_N).$$

The positive recurrent aperiodic states are called ergodic. For an irreducible ergodic Markov chain,  $\lim_{n \rightarrow \infty} P_{i,j}^n$  exists and is independent of  $i$ . Furthermore, let

$$\pi = \pi P \text{ or } \pi_j = \sum_i \pi_i P_{ij} \text{ or } \pi_j = \sum_i \pi_i a_{ij},$$

$$\pi_1 = a_{N1} \pi_N = \pi_N,$$

$$\pi_j = \sum_i \pi_i a_{ij} = \sum_{1 \leq i < j} \pi_i a_{ij},$$

$$\pi_2 = \pi_1 a_{12},$$

$$\pi_3 = \pi_1 a_{13} + \pi_2 a_{23}, \quad (14)$$

$$\pi_3 = \pi_1 a_{13} + \pi_1 a_{12} a_{23},$$

$$\pi_3 = \pi_1 (a_{13} + a_{12} a_{23}),$$

$$\pi_4 = \pi_1 a_{14} + \pi_2 a_{24} + \pi_3 a_{34},$$

$$\pi_4 = \pi_1 a_{14} + \pi_1 a_{12} a_{24} + \pi_1 (a_{13} + a_{12} a_{23}) a_{34},$$

$$\pi_4 = \pi_1 \{a_{14} + a_{12} a_{24} + a_{13} a_{34} + a_{12} a_{23} a_{34}\}.$$

From the above calculations, we can make a generic equation for  $j \geq 3$  as follows:

$$\pi_j = \pi_1 \left[ a_{1j} + \sum_{k=2}^{j-1} \prod_{1 < b_1 < \cdots < b_{k-1} < j} a_{1b_1} a_{b_1 b_2} \cdots a_{b_{k-1} j} \right]. \quad (15)$$

Now, we will show that the above relation is valid using induction:

(i)  $j = 3$ 

$$\pi_3 = \pi_1 \left[ a_{13} + \sum_{k=2}^2 \prod_{1 < b_1 < b_3} a_{1b_1} a_{b_1b_3} \right], \quad (16)$$

$$\pi_3 = \pi_1 (a_{13} + a_{12}a_{23}). \quad (17)$$

(ii) We assumed that (16) is valid for  $j \leq n$ . Therefore, let us prove this relation is valid:

$$\pi_{n+1} = \sum_{i=1}^n \pi_i a_{i(n+1)}, \quad (18)$$

$$\pi_{n+1} = \pi_1 a_{1n+1} + \pi_2 a_{2n+1} + \sum_{i=3}^n \pi_i a_{i(n+1)}, \quad (19)$$

$$\pi_{n+1} = \pi_1 a_{1n+1} + \pi_1 a_{2n+1} + \sum_{i=3}^n \pi_1 a_{i(n+1)} \cdot \left[ a_{1i} + \sum_{k=2}^{i-1} \prod_{1 < b_1 < \dots < b_{k-1} < i} a_{1b_1} a_{b_1b_2} \dots a_{b_{k-1}i} \right], \quad (20)$$

$$\pi_{n+1} = \pi_1 a_{1n+1} + \pi_1 \sum_{i=2}^n a_{1i} a_{i(n+1)} + \sum_{i=3}^n \pi_1 a_{i(n+1)} \cdot \sum_{k=2}^{i-1} \prod_{1 < b_1 < \dots < b_{k-1} < i} a_{1b_1} a_{b_1b_2} \dots a_{b_{k-1}i}. \quad (21)$$

We simplify the last part of (21):

$$\begin{aligned} &= \pi_1 \sum_{i=3}^n \sum_{k=2}^{i-1} \prod_{1 < b_1 < \dots < b_{k-1} < i} a_{1b_1} a_{b_1b_2} \dots a_{b_{k-1}i(n+1)} \\ &= \pi_1 \sum_{k=2}^{n-1} \prod_{1 < b_1 < \dots < b_k < n+1} a_{1b_1} a_{b_1b_2} \dots a_{b_{kn+1}}, \end{aligned} \quad (22)$$

$$\begin{aligned} \pi_{n+1} &= \pi_1 a_{1n+1} + \pi_1 \sum_{i=2}^n a_{1i} a_{i(n+1)} \\ &\quad + \pi_1 \sum_{k=2}^{n-1} \prod_{1 < b_1 < \dots < b_k < n+1} a_{1b_1} a_{b_1b_2} \dots a_{b_{kn+1}}. \end{aligned}$$

Let  $k+1 = k'$ . Consider

$$\begin{aligned} \pi_{n+1} &= \pi_1 a_{1n+1} + \pi_1 \sum_{i=2}^n a_{1i} a_{i(n+1)} \\ &\quad + \pi_1 \sum_{k'=3}^n \prod_{1 < b_1 < \dots < b_{k'-1} < n+1} a_{1b_1} a_{b_1b_2} \dots a_{b_{(k'-1)(n+1)}}, \end{aligned} \quad (23)$$

$$\pi_{n+1} = \pi_1 \left\{ a_{1n+1} + \pi_1 \sum_{k'=2}^n \prod_{1 < b_1 < \dots < b_{k'-1} < n+1} a_{1b_1} a_{b_1b_2} \dots a_{b_{(k'-1)(n+1)}} \right\}.$$

Since  $\sum_i \pi_i = 1$ , we have

$$\begin{aligned} \sum_{i=1}^N \pi_i &= \pi_1 + \pi_1 a_{12} \\ &\quad + \sum_{i=3}^N \pi_1 \left\{ a_{1i} + \sum_{k=2}^{i-1} \prod_{1 < b_1 < \dots < b_{k-1} < i} a_{1b_1} a_{b_1b_2} \dots a_{b_{k-1}i} \right\}, \end{aligned} \quad (24)$$

$$\begin{aligned} \frac{1}{\pi_1} &= 1 + a_{12} \\ &\quad + \sum_{i=3}^N \left\{ a_{1i} + \sum_{k=2}^{i-1} \prod_{1 < b_1 < \dots < b_{k-1} < i} a_{1b_1} a_{b_1b_2} \dots a_{b_{k-1}i} \right\}, \end{aligned}$$

$$\begin{aligned} m_{1,N} &= m_{1,1} - 1, \\ m_{1,N} &= \frac{1}{\pi_1} - 1, \\ m_{1,N} &= a_{12} \\ &\quad + \sum_{i=3}^N \left\{ a_{1i} + \sum_{k=2}^{i-1} \prod_{1 < b_1 < \dots < b_{k-1} < i} a_{1b_1} a_{b_1b_2} \dots a_{b_{k-1}i} \right\}. \end{aligned}$$

Figure 4 describes the overall opportunistic transmission flow strategy. When the sender transmits the data to the receiver, the algorithm assigns the priorities according to the node's distance from the receiver. The highest priority node is always the receiver, and the next highest priority is allocated to the node that is nearest to the receiver, and so on. If the highest priority node fails to receive the data or to transmit the data to the receiver, then the next highest priority node will try to transmit the data to the receiver. According to this flow chart, we have developed our probabilities, considering the success and failure probabilities of all possible paths to the destination. The final outcome of the equations is shown in (8) described in the previous section.

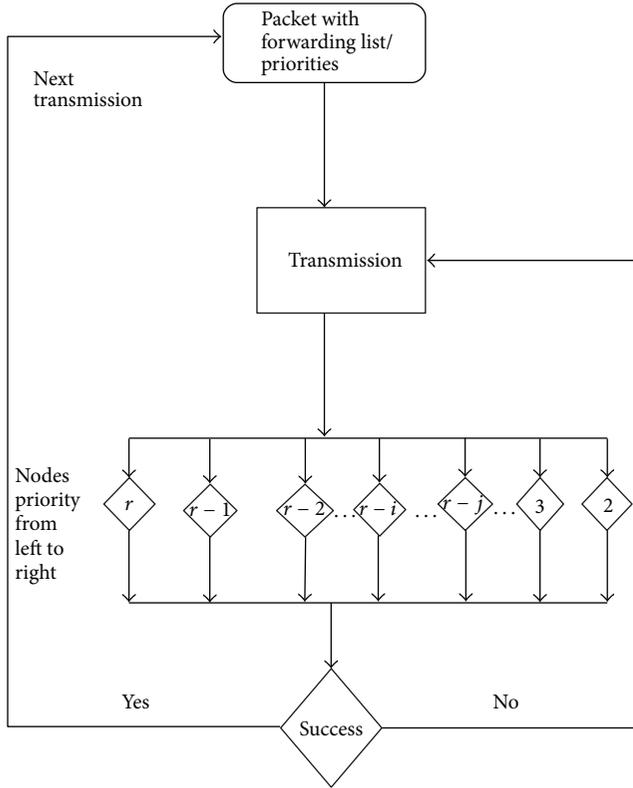


FIGURE 4: System flow chart.

TABLE 1: Nodes versus distance for multihop transmission.

Nodes	Distance/success probability				
	40	80	120	160	200
3	0.993696	0.964859	0.906123	0.816797	0.702214
5	0.997767	0.987432	0.965747	0.930953	0.882508
8	0.999035	0.994552	0.985058	0.969567	0.947442
11	0.999435	0.996805	0.991222	0.982063	0.968875
15	0.999659	0.99807	0.994691	0.989133	0.981093

#### 4. Results and Discussion

We set the following parameters for our simulation for this scenario.  $P_T$  is set to 1,  $\alpha$  is 2.5, and we increase the number of relay nodes between source and receiver to see the impact on the probability of success.

The impact of distance on the probability of success for multihop is depicted in Table 1. It can be seen that the probability of success decreases with increasing distance for different numbers of nodes. When the distance between sender and receiver exceeds a certain threshold, it decreases the probability of success. Moreover, the signal amplitude is decreased with increasing propagation distance. In case of failure of transmission of multihop transmission, transmission needs to follow the same path again until the data is successfully transmitted.

Table 2 shows the impact of distance on the probability of success for OT. It is clearly seen that the probability of success

TABLE 2: Nodes versus distance for opportunistic transmission.

Nodes	Distance				
	40	80	120	160	200
3	1	0.999969	0.999409	0.99556	0.98055
5	1	0.999626	0.996542	0.99590	0.98199
8	1	0.9999	0.998949	0.99611	0.98362
11	1	1	0.999522	0.99683	0.98521
15	1	1	0.999777	0.998402	0.99174

TABLE 3: ETX for multihop transmission.

Nodes	Distance/ETX				
	40	80	120	160	200
3	1.006344	1.036421	1.103603	1.224295	1.424067
5	1.002238	1.012728	1.035468	1.074168	1.133134
8	1.000966	1.005478	1.015169	1.031388	1.055473
11	1.000566	1.003205	1.008856	1.018265	1.032125
15	1.000342	1.001933	1.005337	1.010987	1.019271

TABLE 4: ETX for opportunistic transmission.

Nodes	Distance/ETX				
	40	80	120	160	200
3	1	1.000031	1.000591	1.019459	1.019831
5	1.00001	1.000374	1.00347	1.018008	1.016969
8	1.000003	1.0001	1.001052	1.006382	1.015093
11	1.000001	1.000043	1.000479	1.003180	1.013006
15	1	1.000019	1.000223	1.001601	1.008325

is reduced as the distance increases. If we compare the values with multihop transmission, the probability of success for OT is higher than multihop in all cases. The probability of success decreases with increasing distance, but the impact is very low for OT. The main reason is that if one of the possible paths to the destination fails, there are other paths that can lead to successful delivery of the data. The number of paths to the destination increases with an upsurge in the number of nodes in a network, which increases the probability of success.

The impact of distance on the expected number of transmissions for multihop is shown in Table 3. It can be seen that ETX increases in proportion to increasing distance.

The expected number of transmissions for opportunistic transmission is presented in Table 4. It is clearly seen that the impact of distance results in more transmissions. In comparison with multihop transmission, OT requires fewer transmissions to successfully deliver the data.

Figure 5 shows the outcome of increasing transmission power on the probability of success. The probability of success rises with increased power for multihop and opportunistic transmission. Opportunistic transmission outperforms multihop transmission.

It is clearly seen from Figure 6 that the number of transmissions decreases as we increase transmission power. OT performs better than traditional multihop transmission. The outcome shows that OT is more efficient approach to deliver

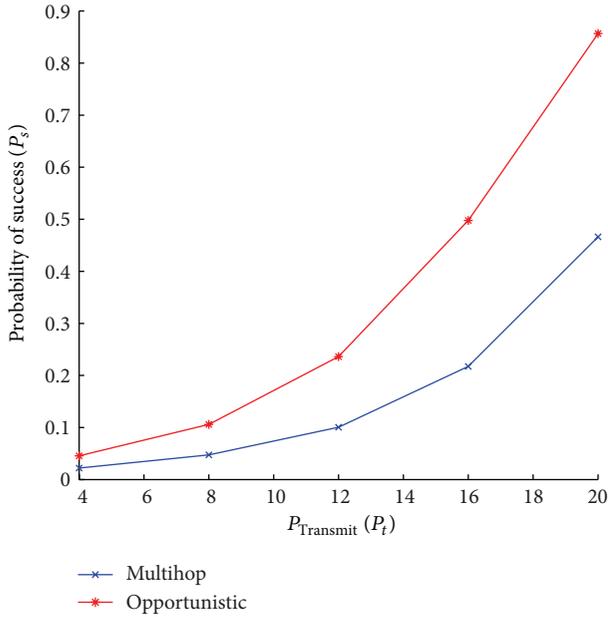


FIGURE 5: Effect of transmission power on  $P_s$ .

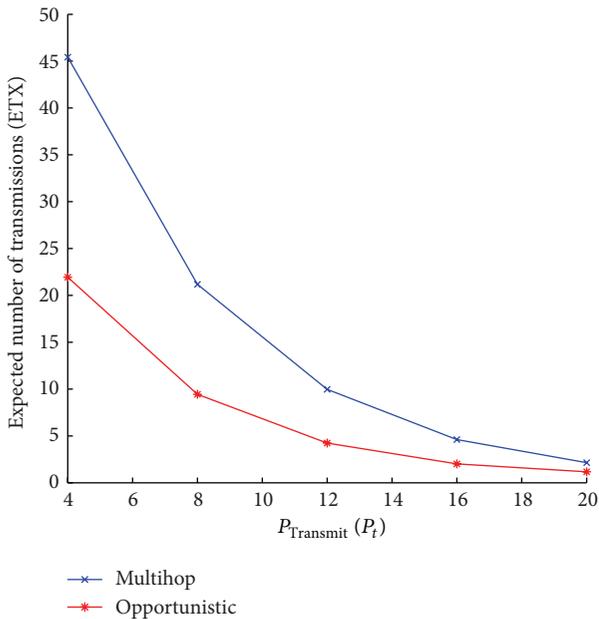


FIGURE 6: Effect of transmission power on ETX.

the data to the destination in fewer transmissions. Further, it reduces the energy consumption due to the less packet losses and retransmissions. Therefore, OT reduces the energy consumption and keeps the most important resource of sensors for a long period of time for communications. Consequently, maximizing the lifetime of the resource constrained cognitive radio sensor networks. Hence, the overall performance of the cognitive radio sensor networks is enhanced.

## 5. Conclusion

Two types of transmission have been studied in this paper, multihop and opportunistic. More specifically, a fixed-distance-based statistical model is proposed for multihop and OT for cognitive radio sensor networks. Additionally, the unique generic Markov chain model is proposed to show the stability of OT. OT shows improvement in reliably delivering the packet in fewer transmissions in contrast to multihop transmission. Hence, OT successfully delivers the data in an energy efficient way, increases the sensor's lifetime, and improves overall system performance. It opens a new direction for multihop cognitive radio sensor networking-related research.

We will extend this statistical analysis for random-distance intermediate node scenarios. We will also work on a cross-layer protocol design by incorporating these statistical analyses.

## Conflict of Interests

The authors declare no conflict of interests.

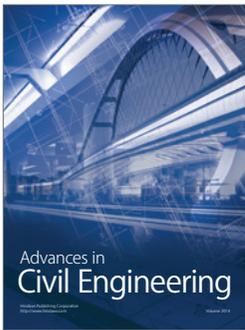
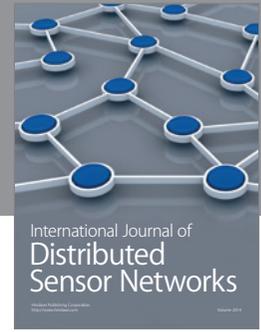
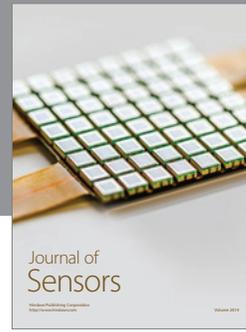
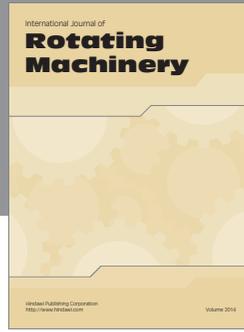
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