

Predict the Multi-hop Reliability for Receiver-Contention Based Routing in Dynamic Link Networks

Yongcai Wang, Yuexuan Wang, and Dazhong Zheng

Abstract—We consider dynamic link networks(DLN), where nodes are static, but the links are highly dynamic. Reliable multi-hop communication is critical in such networks, which inspires receiver contention routing, which elects relays from actual receivers to overcome link dynamics. However, in previous studies of receiver contention routing protocols, the multi-hop reliability is lack of deep understanding, because the randomness and redundancy in the multi-hop packet forwarding process are hard to model.

We propose RECORD protocol to control the randomness and redundant packet for receiver contention, which is carried out by designing sector-shape forwarding zone, prioritized CTS, and contention clearing scheme. For symmetric link DLNs, RECORD can guarantee multi-hop unique-path routing, which enables a Markov Chain model to the multi-hop forwarding process. The multi-hop reliability is predicted by analyzing the stable status of the Markov chain. Particularly, when positions of all sensors are known, the multi-hop reliability of RECORD has close-form formula; when node positions are unknown, recursive upper bound and lower bound are derived. Further, RECORD is implemented distributively by both simulation and in real sensor networks. Extensive evaluations validate the analytical results.

Index Terms—Dynamic Link Networks, Markov Chain, Receiver Contention Routing.

I. INTRODUCTION

With popularity of ubiquitous devices, dynamic link networks(DLN) are emerging, where network is ad-hoc; nodes are mainly static, but the links are highly dynamic. Examples of such DLNs can be sensor networks with random on/off sensors, or wireless local networks deployed in subway or shopping mall, whose environment has massive mobile objects. A majority task of DLNs is long range multi-hop communication. For an example, in traffic monitoring network, when a sensor detects traffic jam or an accident, it should inform other far away sensors about the event quickly via multi-hop communication. However, due to the random on/off node scheduling, multi-path fading, interferences, blocks and node failures [5] in the DLNs, multi-hop message delivery rate, denoted as “multi-hop reliability”, is highly unreliable. How

to obtain reliable multi-hop communication on the dynamic links is a challenging issue.

To address above problem, “Receiver contention” forwarding was proposed as a promising solution [11]. In it, the sender doesn’t specify any relay when it broadcasts the message. It only writes destination location into the message, and when neighbors in its forwarding zone (a sub-area of the broadcasting circle) actually receive the message, they compete by some geographical metric to act as the relay node. So the relay is elected among the actual receivers, which overcomes the link dynamics. Receive contention routing has attracted many research interests, such as GeRaF[15][16], IGF[3], ExOR[2], M-GeRaF[9], MACRO[6], PSGR[13], ALBA[4] etc. By paying the cost of location awareness, receiver contention routing can provides many benefits, including multi-hop reliability, high throughput [2], energy efficiency[15][16] etc. Some of these benefits have been thoroughly analyzed, but the multi-hop reliability, which is the most important advantage of receiver contention still lacks quantitative analysis and deep understanding. Only in GeRaF, the expected hop progress is calculated, and only the expected number of hops to reach the destination is evaluated.

Analyzing the multi-hop reliability is difficult because of the randomness and redundant packets in the multi-hop forwarding process. First, since relay in each hop is dynamically elected from receivers within sender’s communication range, the multi-hop routing space is dimension-explosive, with size $O(n^k)$, where k is the number of hops, and n is the expected number of one-hop neighbors. Secondly, actual receivers can hardly agree on one unique relay. Due to link dynamics, some receivers may miss the acknowledgement from others, which generates redundant relay packets. Redundant packets will form disjoint paths, making multi-hop reliability prediction very difficult. At the same time, redundant relay will consume additional energy which should be prevented.

Seeing these challenges, we propose a REceiver-Contention Routing for Dynamic link networks (RECORD) to restrict the route randomness and avoid duplicate packets for receiver contention. RECORD exploits the ideas of 1) $\pi/3$ sector shape forwarding zone; 2) prioritized CTS acknowledgement, and 3) contention clearing scheme using preamble of relay message. RECORD generates a reliable single path for multi-hop data transmission. Although single path routing is less reliable than the multi-path routing, it is more energy efficient. More importantly, it enables the prediction of multi-hop reliability of receiver contention routing. This guides system design before

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real system deployment.

In RECORD, a “state transition” model is built to model the one-hop relay process, and a Markov Chain model is built for the multi-hop forwarding process. By analyze the Markov Chain, we show its special feature, that the Markov Chain has only two absorbing states: 1) the message is lost; 2) the message finally reaches the destination. By analyzing the proportion of these two absorbing states in the stable status of the Markov Chain, the multi-hop reliability is formally addressed. Particularly, we prove that 1).when the positions of all the sensors are known, the multi-hop reliability of RECORD has a close form formula; 2) when node locations are unknown, upper bound and lower bound of the multi-hop reliability are functions of the node density and source-destination distance. The Markov Chain model is flexible, which can be further improved to model multi-path and duplicate packets by changing the state transition matrix to “path quality matrix”, for which, we provide the first step investigation. From our simulations and real experiments in sensor network, the multi-hop reliability formulas and the derived bounds are validated by statistical results.

The rest of this paper is organized as follows: RECORD and the state transition model are introduced in Section 2, based on which, the Markov Chain model and the multi-hop reliability analysis are presented in Section 3. In Section 4, the upper bound and lower bound of multi-hop reliability in case of not knowing node positions are presented. Simulation and experimental results are reported in Section 5. Related work is discussed in Section 6, and Section 7 concludes with some future plans.

II. RECORD AND ONE-HOP MODEL

A. Dynamic Link Network

The dynamic link network (DLN) is modeled by a dynamic graph: $G = (V, E)$, where the vertex set V is static, but the edge set E is dynamic. We propose the link existing probability (LEP) to model the link dynamics. For a node i and a node j , LEP is defined as a function of the distance, i.e., a function of $d_{i,j}$:

$$L_{i,j} = I|_{r < Prr(d_{i,j})} \quad (1)$$

Where $r \in [0, 1]$ is a randomly generated variable. $Prr(d_{i,j})$ is the message reception rate when the message propagates distance $d_{i,j}$. In DLN, when node i is sending message and node j is listening, if r is generated to be less than $Prr(d_{i,j})$, the link between i and j exists, i.e., $L_{i,j}=1$; otherwise the link doesn't exist, and $L_{i,j}=0$.

There are different kinds of packet reception rate models[?][5]. In this paper, we use an empirical packet reception rate model, which is proposed in [17], because it is well accord with practical channel conditions. The model counts three aspects of randomness in wireless communication: multi-path fading error, encoding error, noise floor of SNR.

$$Prr(d) = \left(1 - \left(\frac{1}{2}\right) \exp^{-\frac{\varphi(d)}{1.28}}\right)^{\eta 8f} \quad (2)$$

where d is the distance from sender to receiver; φ is the signal to noise ratio (SNR) related with the RF power and

the transmission distance, η is the encoding ratio and f is the frame length.

In addition, we make three assumptions. 1) Limited communication range. A threshold R exists, beyond which, packet reception rate is zero, i.e., $Prr(d) = 0$, if $d > R$. 2) Slow link variation assumption. We assume links don't vary within very short time, because environments commonly don't change very fast. 3) Symmetric link assumption. When A can reach B, then B can reach A.

B. RECORD Protocol

To overcome message loss on the dynamic links, RECORD is proposed for Receiver-Contention Routing on Dynamic link networks. It is designed with two aims: 1) reliable hop by hop communication on dynamic links; 2) redundant forwarding avoidance for energy efficiency and state transition modeling.

In RECORD, when a sender s is sending a message, it does carrier sense to wait until the channel is clear. Then it broadcasts a RTS in which, the sender's location and the destination's location are written in. When a neighbor in its **forwarding zone** actually receives the RTS, it calculates its **relay priority** based on the location information in RTS and its own location, and responses a CTS message after a very small delay. The **delay time** is generated by a decreasing function of the **relay priority**. The actual receiver with the highest relay priority will response CTS first. When the sender receives the first CTS from the highest priority receiver, it selects this receiver as the **relay**, and immediately sends data to this relay. When the CTS from this relay is heard by other actual receivers, they cancel their CTS clock to avoid redundant forwarding. In case some actual receivers miss the CTS from the relay node, their forwarding attempt will still be canceled by hearing the preamble of the data message from the sender.

1) The forwarding zone. In RECORD, the forwarding zone of a sender is defined as a $\pi/3$ sector area, centered at the sender, with radius R , and is axial symmetry to the source-destination direction. As shown in Figure 1, the gray fan-shaped areas are forwarding zones of node O and node A respectively. $\pi/3$ sector area is designed for energy efficiency and redundancy avoidance, because all relay candidates are within communication range of each other. The CTS from the highest priority relay candidate has high probability to be heard by low priority relay candidates to cancel their CTS clock. In case some relay candidates miss the CTS, their relay attempts will still be canceled by the preamble of the data message. This provides unique path forwarding, but is not delivery guaranteed. In case one-hop transmission fail, we can increase the sector radius (R) to enlarge the forwarding zone for recovery. In this paper, we focus the communication reliability of **basic RECORD**, route recovery and retransmission is left to future work.

2). The relay priority. The relay priority is calculated by **relay progress** and **relay angle**. Relay progress is defined as the projection of the sender-receiver distance onto the source-destination direction, which is calculated using source, destination locations in RTS and the node's own location.

Relay angle is defined as the angle between sender-receiver direction and the sender-destination direction. As shown in Figure 1, $\xi_1 = \|\text{OA}_1\|$ is the relay progress of the receiver A, and α_1 is the relay angle of A. The relay priority is generated by a decreasing function of the relay process ξ , and it is an increasing function of the relay angle α .

$$T(\xi, \alpha) = (R - \xi + \alpha \cdot \omega) \cdot \tau \quad (3)$$

where τ is a constant time slice. ω is a parameter to adjust the weights of α and ξ . The smaller the $T(\xi, \alpha)$ is, the higher the relay priority.

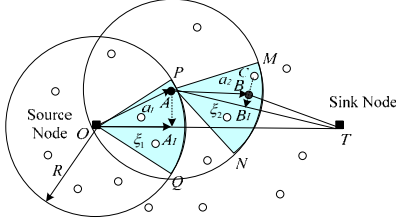


Fig. 1. RECORD for message forwarding.

C. One-hop State Transition Model

For symmetric links, only if there is one actual receiver in the forwarding zone, can RECORD guarantee packet forwarding without redundancy. This shows Markov property if we model the message forwarding process as state transition. We denote the *message position* at hop k i.e., the position of the node who is currently holding the message as the **state of hop k** . So the number of states in hop k must be countable. The state changes when message forwarding happens. The state at hop k is only determined by the state at hop $k-1$ and the link dynamics in this hop, which is irrelevant to the previous hops. Therefore, the message forwarding process of RECORD shows Markov property.

Considering an instance, when the current sender is s , and there are n relay candidates in the forwarding zone of s . These n nodes are denoted by $\{r_1, r_2, \dots, r_n\}$ following a descending order according to their relay priorities. The distances from these relay candidates to the source node are denoted by $\{\delta_1, \delta_2, \dots, \delta_n\}$. Now we calculate the one-hop state transition probability.

If the receiver contention result is the node with the priority i relays the message, it must be because that all the relay candidates r_1 to r_{i-1} fail to receive the RTS, and only r_i receives the RTS. So the probability that the packet is relayed by the node r_i can be calculated as:

$$p_s(\delta_i) = Prr(\delta_i) \prod_{j=1}^{i-1} (1 - Prr(\delta_j)) \quad (4)$$

The one hop failure will occur if all the n relay candidates fail to receive the packet, so the probability that one hop failure happens can be calculated as:

$$\bar{p}_s = \prod_{j=1}^n (1 - Prr(\delta_j)) \quad (5)$$

There are special cases in the last hop. When the destination node is within the forwarding zone, the destination node must have the highest priority. If the distance from the sender to the destination is δ_T , the probability that the packet is successfully received by the destination is $Prr(\delta_T)$. Otherwise, the packet is relayed by RECORD towards the destination. The relay candidates beyond the destination will not be involved in the contention (with negative process). Supposing there are m relay candidates (excluding the destination node), we reorder them in a descending order according to their relay priorities and denote them $\{r_1, r_2, \dots, r_m\}$. The distances from them to the sender are denoted by $\delta_1, \delta_2, \dots, \delta_m$. If the contention result is that the node r_i relays the packet, it must be because that all the nodes r_1 to r_{i-1} fail to receive the packet. The probability that the packet will be relayed by node r_i is:

$$p_s(\delta_i) = (1 - Prr(\delta_T)) Prr(\delta_i) \prod_{j=1}^{i-1} (1 - Prr(\delta_j)) \quad (6)$$

The probability of one hop failure in the last hop can be calculated if all the nodes fail to receive the packet.

$$\bar{p}_s = (1 - Prr(\delta_T)) \prod_{j=1}^m (1 - Prr(\delta_j)) \quad (7)$$

So the one hop state transition probabilities can be calculated.

III. MULTI-HOP RELIABILITY WITH LOCATION INFO

In this section, we consider the multi-hop reliability when node positions are known. First, analysis in 1-D networks is presented hoping to bring out the key underlying concepts.

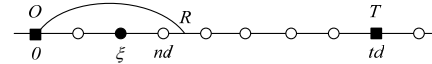


Fig. 2. One-dimensional network with equal node distance

A. Reliability Analysis in 1-D Network

Consider the simple 1-D network with nodes deployed on a line. The distances between adjacent nodes are equal, which is denoted by d . The source node O locates at the origin and the destination node T locates at position td . Fig.2 shows the scenario. In the 1-D network, if the location of current sender is id and $id \leq td - R$ the forwarding zone of this sender is just the segment $(id, id+R]$. If $(td-R) < id < td$, the destination is within the forwarding zone of the sender. The forwarding zone is the segment $(id, td]$. We denote n_i as the number of sensors in the forwarding zone. Then n_i can be calculated by $n_i = \min\{\lfloor R/d \rfloor, t - i\}$, where $\lfloor \cdot \rfloor$ is the floor operation.

The Markov States for the 1-D network can be listed as $(1, 2, \dots, t+1, t+2)$, in which, state i means that the packet is at position $(i-1)d$; state $t+1$ means the packet reaches destination, and state $t+2$ means the message is *lost*; Fig.3 shows the Markov Chain model. The circles stand for the states. The arcs between states mean the possible transitions. The values on the arcs are the transition probabilities. If a packet reaches the destination or is lost, it will stay in the

state and can not transmit to the other states, so both the state $t+1$ and the state $t+2$ are absorbing states. For other states, if the packet leaves this state, it will never come back, so states $1 \sim t$ are transient states.

Consider the transition probability from state i to state j , which can be calculated by Eqn.(4)-Eqn.(7). We summarize them in Eqn.(8).

$$p_{i,j} = \begin{cases} p_i((j-i)d) & 1 \leq j-i \leq n; i \neq t+1, t+2; j \neq t+2 \\ \bar{p}_i & j = t+2; i \neq t+1; i \neq t+2 \\ 1 & i = j = t+1, \text{ or } i = j = t+2 \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

So the state transition matrix can be formulated as Eqn.(9):

$$P = \begin{pmatrix} 0 & P_{1,2} & \cdots & P_{1,n} & 0 & \cdots & 0 & P_{1,t+2} \\ 0 & 0 & \cdots & P_{2,n} & P_{2,n+1} & \cdots & 0 & P_{1,t+2} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \cdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & P_{n,n+1} & \cdots & P_{n,t+1} & P_{n,t+2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \ddots & P_{t,t+1} & P_{t,t+2} \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (9)$$

It is easy to verify that $\sum_{j=1}^{t+2} P_{i,j} = 1$, so P a transition probability matrix. Because the packets are forwarded towards a unique direction, P is an **upper triangular matrix**. For all $j \leq i$, we have $P_{i,j} = 0$, except $P_{t+1,t+1} = 1$ and $P_{t+2,t+2} = 1$ (the absorbing states).

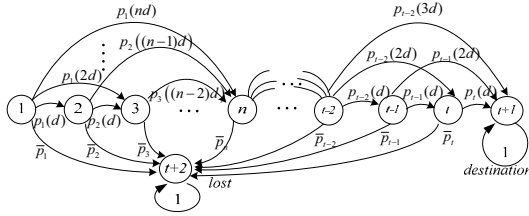


Fig. 3. The Markov Chain model for the multi-hop forwarding in 1-D network

P provides the one-hop state transition probability, and the n th power of P , i.e., P^n will provide state transition probability of the n -hop paths. For example $(P^n)_{i,j}$ means that if the initial state of the packet is i , after n hops of packet forwarding, the packet has probability $(P^n)_{i,j}$ to be at the state j .

For the scenario shown in Fig. 1, the initial position of the message is at the origin, i.e., the initial state is 1. The target state is $t+1$. So the longest path is at most t hops. Since the state $1 \sim t$ are all transient states (P is upper triangular), after t times of state transition, the Markov Chain reaches its stable status, i.e., $P^t = P^{t+1}$. Its stable status has special feature: 1). for all i and j , $(P^t)_{i,j} = 0$, except that $(P^t)_{1,t+1}$ and $(P^t)_{1,t+2}$ are not zero; 2) $(P^t)_{1,t+1} + (P^t)_{1,t+2} = 1$.

That is, there are only two fates for any message, 1) been successfully transmitted to the destination (absorbed to state $t+1$), or 2) been lost (absorbed to state $t+2$). $(P^t)_{1,t+1}$ means the probability that the packet is eventually transmitted

from the source to the destination and $(P^t)_{1,t+2}$ means the probability that the packet is eventually lost. We formulate these results as Theorem 1.

Theorem 1: For 1-D network with equal node distance, when source is at 0, and the target is at td , the t -hop reliability performance is:

$$\gamma = (P^t)_{1,t+1} \quad (10)$$

The average multi-hop failure probability is

$$1 - \gamma = (P^t)_{1,t+2} \quad (11)$$

where P is calculated from Eqn.(9), $t+1$ is the message reception state, and $t+2$ is the message lost state.

B. Reliability Analysis in 2-D Network

The multi-hop packet forwarding process in the 2-D networks is also a Markov Process. But in the 2-D network, the condition is more complex. We cannot enumerate the states of the Markov Chain by simply observing the network topology. Because of the fan-shaped forwarding zone, some nodes far away from the source and the destination may not participate in message forwarding. Their positions should not be counted as the states.

1) *Transition Probability Matrix Construction* : From the one hop model, we see that if the current sender is specified, the possible states of the message in the next hop are the receivers' locations in its forwarding zone. So the locations of these receivers should be added into the state space. Therefore, we can construct the state space step by step by exploring the forwarding zone of every sender in every round. Based on this idea, we propose a transition probability matrix construction algorithm.

We denote Z as the state space, which initially contains only three states: $\{O, T, lost\}$. We denote n the size of the state space. Initially $n = 3$. We divide the state space Z into two parts. The first part is the sender set, denoted by S . The second set contains only $\{T, lost\}$. A unique index is assigned to every node in S . Initially $S = \{s_1\} = \{O\}$. The currently exploring sender is denoted by s_c , and initially $c=1$. We denote the relay candidate set of s_c as $R(s_c)$, and denote the relay candidate by $r_k \in R(s_c)$. The newly discovered states in $R(s_c)$ are stored into M . The transitional probability matrix is denoted by P , which is $n \times n$ matrix. We denote the set of the explored senders as E . Initially, E is empty. In Algorithm1, line 2 initializes M and m before exploring the sender's forwarding zone. Line 3-8 is to explore the forwarding zone of current sender to search new states. Line 9-16 is to fill the transition probability matrix after finding new states. Line 17 is to update the state space. Line 18 is to update the sender set and line 19 is to label current sender to be "already explored". Line 20 is to update the index of current sender. With Algorithm 1, the state space can be explored and the transition probability between any two states can be calculated. Thus, the state space Z and the transition matrix P are obtained.

Algorithm 1 Transition Probability Matrix Construction Algorithm in the 2-D networks

```

1: while c ≤ sizeof(S) do
2:   M=EMPTY, m=0.
3:   for (k=0;k<sizeof(R(s_c)); k++) do
4:     if (r_k ∉ Z)&&(ξ(r_k) > 0) then
5:       Add r_k into M
6:     end if
7:   end for
8:   m = sizeof(M), n = n + m
9:   Resize P to (n + m) * (n + m)
10:  for (i=1, j=1;i=n, j=n; i++,j++) do
11:    Calculate Pi,j by Eqn.(4)(6), if i = si, j ∈ M
12:    Calculate Pi,j by Eqn.(4)(6), if i ∈ E, j ∈ M
13:    Pi,j = 0, if i ∈ T, lost, j ∈ M
14:    Pi,i = 0, if i ∈ M
15:    Pi,j = 0, if i ∈ M, j ∈ E
16:  end for
17:  Z = Z + M
18:  S = S + M
19:  E = E + s_c
20:  c = c + 1
21: end while

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2) *Multi-hop Reliability Performance* : The matrix P indicates one hop transition probabilities. n hop transition probabilities can be calculated by the n th power of P , i.e., P^n . To obtain the similar reliability expression as the Eqn.(10), there are two questions to be answered:

1) Is the state space limited? 2) If the state space has limited n states (including *lost*), is P^n stable, i.e., is $P^n = P^{n+1}$?

The first question is easy to answer. Since the number of nodes is limited in the 2-D region, the state space must be limited. To answer the second question, we only need to prove that there is no loop path in RECORD. After n hops of relay, the message must have entered absorbing states. Lemmal states the no loop path character.

Lemma 1: If i and j ($i \neq j$) are two states in Z and P_{ij} is the transition probability from state i to state j , if $P_{ij} > 0$, it must hold that $P_{ji} = 0$.

Proof: P_{ij} stands for the transition probability when the node i is the sender and the node j is a receiver. if $P_{ij} > 0$, j is in the forwarding zone of i . To prove $P_{ji} = 0$, we only need to prove i is not in the forwarding zone of j . We consider the relationship of i and j as shown in Fig.4. When j is in the forwarding zone of i , only when $\angle Dj i \leq \pi/6$, the node i can be in the forwarding zone of the node j . If this really happens, there must be $\angle j D i \geq 2\pi/3$. This case cannot happen in RECORD because the negative relay progress. So the node i cannot be within the forwarding zone of the node j . Therefore, if $P_{ij} > 0$ and $i \neq j$, it must hold that $P_{ji} = 0$. ■

With Lemma1, we know that there is no loop path in RECORD protocol. If there are totally n states in the state space(including T and *lost*), the longest path is at most $n - 2$ hops. So after $n - 2$ times of the packet forwarding, a packet is eventually forwarded to the destination node, or is lost. So $(P^{n-2})_{i,j} = 0 \quad \forall j \notin \{T, \text{lost}\}$, i.e., only the last two

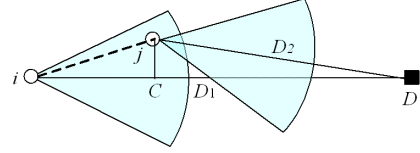


Fig. 4. The illustration of the non-loop path

columns in P^{n-2} contain positive values. The values in the last columns will stay stable because the states $\{T, \text{lost}\}$ are absorbing states, so P^x will remain stable for all $x \geq n - 2$: $P^x = P^{x+1}$. So the multi-hop reliability for 2-D network is formulated as a Theorem.

Theorem 2: The multi-hop reliability performance of 2-D network is:

$$\gamma = (P^{n-2})_{1,n-1} \quad (12)$$

The probability that the packet is eventually lost is:

$$1 - \gamma = (P^{n-2})_{1,n} \quad (13)$$

where P is the transitional probability matrix constructed by Algorithm 1. n is the size of state space. The n th state is message lost and the $(n - 1)$ th state is reaching destination. So that the multi-hop reliability performance can be evaluated with location information.

IV. MULTI-HOP RELIABILITY ANALYSIS WITHOUT NODE LOCATION

In real applications, location information of the sensors is not easy to obtain. A more general case is to estimate the average multi-hop reliability performance without the location information. Consider a battlefield application. Sensors are randomly deployed into a region to observe an enemy target, which is at distance D from our base station. We hope the observation packets can be received by our base station with average reliability higher than 0.9. If we deploy sensors with density ρ , can the deployment satisfies our requirement? The problem is to evaluate the average reliability performance when the location information of the sensors is unknown.

A. Slicing The Forwarding Zone

Suppose the sensors are randomly distributed throughout the sensing field according to a Poisson process with density ρ nodes per unit area. The distance between the source node and the destination node is D , then, the average multi-hop reliability performance is a function of ρ and D . We denote it as $\gamma(\rho, D)$. Since the positions of the sensors are unknown, it is difficult to give an accurate analysis of $\gamma(\rho, D)$. But we can use the recursive method to compute an upper bound and a lower bound for the average multi-hop reliability, denoted by $\bar{\gamma}(\rho, D)$ and $\underline{\gamma}(\rho, D)$ respectively. With these bounding results, we can estimate whether a network can satisfy the reliability requirement or not, and use the results to direct our deployment.

We quantize the whole range of possible distances between the source node and the destination. Let d be length of the

quantization interval and v be the number of quantization intervals per unit distance. The total number of intervals considered is $Dv = D/d$ (for analytical convenience, we assume that D contains an integer number of such quantization intervals). More specifically, let $\Delta_i = ((i-1)d, id]$, $i = 1, 2, \dots, Dv$ be the i th interval. We suppose if the distance between a transmitter and the destination node is less than d , i.e., the source node is within $\Delta_1 = (0, d]$ the average reliability is 1. We consider the case that the source node is at distance id , $i > 1$, as shown in Fig.5. Only the sensors in the forwarding

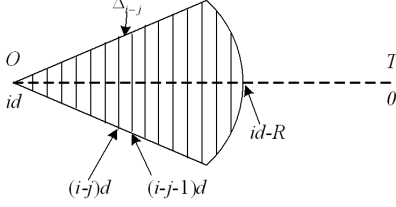


Fig. 5. Slicing the forwarding zone of the sender

zone of the sender can act as the relay. We denote the probability that the advancement will lead to a relay in Δ_{i-j} as $w(i, j)$. In fact, going from id to a point in Δ_{i-j} corresponds to have no actual receivers with relay process $\xi > (j+1)d$, but at least one relay with relay process $\xi > jd$. With link model of sensors described in Eqn.1, the expression of $w(i, j)$ can be derived. For fluency of the expression, we leave the derivation process of $w(i, j)$ in Appendix 1, and propose the recursive upper bound and lower bound in this section.

B. Recursive Upper Bound and Lower Bound

1) *Optimistic Bound:* Consider first an optimistic bound, in which, whenever the relay is in Δ_{i-j} , the remaining distance to destination is set to the minimum possible value $(i-j-1)d$. In this case we can obtain following recursive relationship of the optimistic bound for reliability performance. If the source node is at distance D , we first analyze the case when $D \leq R$.

If the source node and the destination node is within one hop distance, the probability that the packet is directly received by the destination node is $Prr(D)$. If the destination node fails to receive the packet directly, the packet will be forwarded toward the destination with RECORD scheme.

$$\overline{\gamma(\rho, D)} = Prr(D) + (1 - Prr(D)) \cdot \sum_{j=0}^{\min(Rv, D)} w(D, j) \overline{\gamma(\rho, D - (j+1)d)} \quad (14)$$

In (14), $w(D, j)$ is the transition probability from D to a node within $\Delta_{D/d-j}$. For the case when $D > R$, the packet will be relayed toward the destination by RECORD:

$$\overline{\gamma(\rho, D)} = \sum_{j=0}^{Rv} w(D, j) \overline{\gamma(\rho, D - jd - d)} \quad (15)$$

The initial condition is $\overline{\gamma(\rho, d)} = 1$. With (14) and (15), the optimistic bound for any D can be calculated recursively.

2) *Pessimistic Bound:* Similarly, we make an pessimistic assumption that whenever the relay is in Δ_{i-j} , the remaining distance is set to the maximum possible value. We denote this maximum possible distance as $\overline{D}_{i,j}$. In the 1-D network, it is simple that $\overline{D}_{i,j} = (i-j)d$. In the 2-D case, $\overline{D}_{i,j}$ is calculated with triangle method. We quantize the value of the maximum remaining distance as $\overline{D}_{i,j} = \lceil \sqrt{(i-j)^2 d^2 + (jd)^2/3} / d \rceil \cdot d$, in which $\lceil \cdot \rceil$ is the ceil operation.

If the source node and the destination node are within one hop distance, the lower bound can be derived similarly like the upper bound:

$$\underline{\gamma(\rho, D)} = Prr(D) + (1 - Prr(D)) \cdot \sum_{j=0}^{\min(Rv, D)} w(D, j) \underline{\gamma(\rho, \overline{D}_{i,j})} \quad (16)$$

If $D > R$, the packet will be relayed by RECORD towards the destination:

The initial condition is $\underline{\gamma(\rho, d)} = 1$, and the pessimistic bound for any D can be calculated recursively.

The average reliability performance $E(\gamma(D, \rho))$ can be bounded as following:

$$\underline{\gamma(\rho, D)} \leq E(\gamma(\rho, D)) \leq \overline{\gamma(\rho, D)} \quad (17)$$

The tightness of these bounds is controlled by the interval of each slice (d).

V. SIMULATION AND EXPERIMENTS

This section presents computer simulation and experimental results for the multi-hop packet reliability performance in 1-D, 2-D sensor networks.

A. Simulation Results

1) *One-Dimensional Simulations:* Simulations are carried out by Matlab by developing a discrete event simulator of RECORD. We first evaluate a 1-D network, where nodes are randomly deployed along a line. Three kinds of node densities are studied, i.e., the average distances between the adjacent nodes are 10m, 15m and 20m respectively. The source-destination distance varies from 25 m to 500 m in above settings. Our aim is to check how the multi-hop reliability is affected by the transmission distance and node density. In simulation, we generate two aspects of randomness to approach real scenario. The first is the link randomness. We use the same radio model as shown in Eqn.(2). The second is the randomness of the network topologies. To reduce the confidence interval, for each point in the simulation results, we randomly generate 500 different topology networks, and run 500 replications of simulation in each network. The mean value of these 25,000 reliability results is used as the simulated multi-hop reliability. We calculate the 95 percent of the confidence interval, which is nearly one percent of the mean value. The analytical results are calculated by Eqn.(10) using the location information of sensors. The analytical result is also mean value of 500 runs of the randomly generated networks. The bounding results are calculated recursively with Eqn.(15) and Eqn.(17) without location information, in which

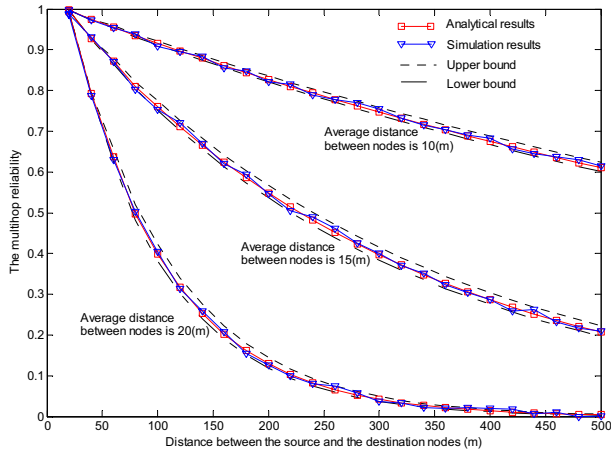


Fig. 6. Multi-hop reliability in 1-D network

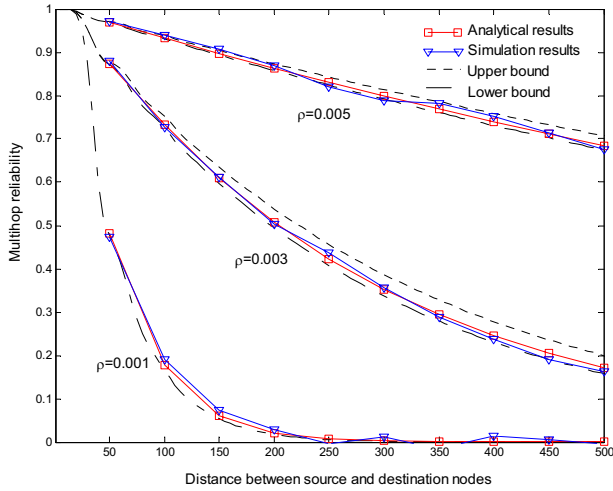


Fig. 7. Multi-hop reliability in 2-D network

the quantization interval d is set to 5. The results are shown in Fig.6. We see that using RECORD, the multi-hop reliability decreases with source-destination distance, and increases with node density. This indicates that receiver contention performs better for dense network. The analytical results and the simulation results closely match, and they are tightly bounded by the optimistic and pessimistic bounds. The results support our analytical derivations and bounding techniques in the 1-D networks.

2) *Two-Dimensional Simulation:* In the 2-D simulations, we investigate the multi-hop reliability performance in a field with $600\text{ m} \times 200\text{ m}$ size. Nodes are uniformly deployed in the field. The distance between the source node and the destination node varies from 25 m to 500 m. The density of the sensors varies from 0.001 to 0.003 and 0.005. Every value in the simulation results is evaluated with 500 replications of simulations in 500 randomly generated networks. The simulation results, analytical results and the bounds are plotted in Fig.7. The multi-hop reliability decreases with source-destination distance, and increases with node density. The close match of the simulation results and the analytical results supports our analytical results in 2-D network. The analytical results and the

simulation results are also tightly bounded by optimistic and pessimistic bounds, showing the effectiveness of the bounds.

B. Experimental Results

We have also carried out experiments to evaluate RECORD using Mica2 nodes. Mica2 nodes are wireless sensor nodes developed by XBow Co.Ltd. The radio module on Mica2 is CC1000. Its working frequency is 960M Hz. The link layer model of Mica2 nodes is studied in [17]. Simple 1-D and 2-D experiments are implemented on a playground to measure the multi-hop reliability performance with RECORD protocol. The results are compared with the analytical results calculated by Eqn.(10) and Eqn. (12).

1) *1-D Experiment:* We deployed Mica2 sensors on a line with equal distance (d) between the adjacent sensors. The distance between the source node and the destination node is denoted by D . D is the integer multiple of d . In every experiment, the source node sends 200 packets to the destination node. The time between each packet is 1 second. The number of packets received by the destination node is counted to measure the multi-hop reliability. In the 1-D experiments, we vary d in the set of $\{15\text{m}, 20\text{m}\}$. D varies from d to $10d$ for every setting of d . The measured reliability results are summarized in Table 1, together with the analytical results.

From the comparison of measured reliability and the analytical results, we saw that the practical implementation achieve reliability performance close to that of analysis. More than that, most of the measured reliability performances are better than the corresponding analytical results. The reason of the close match is not surprised because the link model we used (Eqn.1) is an empirical model. The fading effects have been taken into account. The reason why the measured reliabilities are better is due to the packet redundancy in the real experiments.

In the analysis of the ideal case, we assume symmetric link, so a relay message from a high-priority node can be heard by all the relay candidates, and there is no redundant message. But in the experiments, the CTS response and the relay message may not be heard by all the relay candidates. Some of them may send out a redundant relay message. Although the redundant packet consumes more network resources, it helps to improve the multi-hop reliability performance. The redundant rate was also measured and was summarized in Table 1. The redundant rate increases with the source-destination distance, because more copies of redundant messages will be generated during the multi-hop propagation. So by controlling the redundant rate, the redundant message can be used to improve the multi-hop reliability.

2) *2-D Experiment:* In the 2-D experiments, we deploy 24 Mica2 nodes on two lines. The distance between the two lines is 10 m. The distance between adjacent nodes is denoted by d . The source node and the destination nodes are placed on the two ends of the formed rectangle. The distance between them is denoted by D . D is the integer multiple of d . We vary d in the set of $\{20\text{ m}, 25\text{ m}\}$. D varies from d to $10d$ for every setting of d . The measured reliability results are summarized in Table 2, together with the analytical results. It

TABLE I
THE EXPERIMENT RESULTS OF MULTI-HOP RELIABILITY IN 1-D SENSOR NETWORKS

d (m)	$D=nd$	$1d$	$2d$	$3d$	$4d$	$5d$	$6d$	$7d$	$8d$	$9d$	$10d$
15	Measured	0.93	0.96	0.94	0.98	0.96	1.00	0.92	0.94	0.93	0.94
	Analytical	0.98	0.97	0.96	0.95	0.95	0.94	0.93	0.92	0.91	0.90
	Redundant rate	0.00	0.01	0.04	0.10	0.12	0.16	0.19	0.20	0.22	0.23
20	Measured	0.88	0.82	0.86	0.82	0.80	0.72	0.70	0.66	0.58	0.64
	Analytical	0.93	0.87	0.82	0.77	0.72	0.67	0.63	0.59	0.55	0.52
	Redundant rate	0.00	0.02	0.06	0.11	0.17	0.15	0.19	0.19	0.22	0.25

TABLE II
THE EXPERIMENT RESULTS OF MULTI-HOP RELIABILITY IN 2-D SENSOR NETWORKS

D (m)	$D=nd$	$1d$	$2d$	$3d$	$4d$	$5d$	$6d$	$7d$	$8d$	$9d$	$10d$
20	Measured	1.00	0.99	1.00	1.00	0.98	0.98	0.94	0.96	0.95	0.94
	Analytical	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.90
	Redundant rate	0.05	0.07	0.09	0.13	0.25	0.24	0.23	0.22	0.30	0.33
25	Measured	1.00	1.00	0.96	0.92	0.80	0.72	0.70	0.76	0.78	0.70
	Analytical	0.98	0.97	0.95	0.91	0.82	0.81	0.78	0.74	0.70	0.63
	Redundant rate	0.04	0.06	0.08	0.14	0.19	0.25	0.20	0.29	0.27	0.29

shows that the measured results match well with the analytical results. The packet redundant rate is a little higher than that of the 1-D networks. It is because that there are more sensors in communication region. Because of the redundancy packets, some measured reliability are better than the analytical results. These results support our analytical derivations and show the validity of the proposed practical scheme.

VI. RELATED WORKS

A. Link Dynamics and Multi-hop Reliability

Links in actual wireless networks can be highly unreliable due to multi-path fading, interferences, losses caused by obstacles and random node failure, etc [5]. In [1] the correlated link shadow fading in multi-hop wireless networks is analyzed, which show high correlation of shadow effects. In [14], how the link dynamics affect the delivery rate is analyzed in dense network. In [17] the realistic link quality of wireless sensor network is measured, and an empirical model was proposed, which showed typical transitional region in low power wireless links. In this paper, we use the empirical link proposed in [17], because the empirical model can match real channel condition.

Multi-hop reliability on dynamical links are addressed via different techniques. RTS/CTS handshaking, ARQ (Automatic Retransmission Request) and retransmission schemes are the solutions in the MAC layer to improve multi-hop reliability [7]. Path recovery [4] and multi-path [8] are solutions in the routing layer. Ranking the link reliability with historical data and statistical method can provide a rough estimation of the link qualities. Routing protocols were designed to forward the packets to the sink with good historical reliability [12]. This method is also combined with other contention metric (such as hop distance, etc.) to trade off between the reliability and other performance indices[10]. However these methods improve packet delivery reliability at the cost of introducing complex control, adding more overhead and consuming more energy. In contrast, the receiver contention routing protocols exploited the stateless routing and actual receiver contention to overcome link dynamics, which provide reliable packet delivery without above costs.

B. Receiver Contention Routing

Receiver contention has many research results in the literature. The geographical contention metrics include MFR (Closest to the destination), DIR (Closest direction in radius), and

GEDIR (Largest relay progress) etc., which were summarized in [11]. For protocols, IGF [3] is a representative receiver contention protocol based on volunteer forwarding. The actual receiver in the forwarding zone calculates acknowledgement priority based on the distance to the destination, i.e., using MFR metric. Another famous result is GeRaF (Geographical Random Forwarding) [15][16], in which the actual receivers contend via GEDIR metric. In GeRaF, the hop-count, energy and latency performances are evaluated by the probabilistic method. MARCO [6] provided an integrated MAC/Routing protocol for geographic forwarding. It introduced power control to modify GEDIR metric and proposed “weighted progress”, to contend by progress per unit power. PSGR [13] proposed a priority-based geographical routing, which used dynamical network density estimation to determine contention priorities for receivers. It also addressed the communication void problem (no receiver in forwarding zone). Adaptive Load-Balanced Algorithm (ALBA) [4] prescribes a dynamic coloring scheme aimed at identifying void problem. In these results, the multi-hop reliability performance, which maybe the biggest benefit of receiver contention is seldom addressed. In the basic RECORD protocol proposed in this paper, the design of forwarding zone and relay priority can guarantee single forwarding path, which enables state transition model for multi-hop reliability analysis. The void problem can also be addressed in RECORD by power control, which we leave as future work.

VII. CONCLUSION

We have presented RECORD for reliable communication on dynamic link networks, and have performed analysis to its multi-hop reliability. The contention-based one hop relay is modeled by state transition, enabling a Markov Chain model to the multi-hop forwarding process. By analyzing the proportion of absorbing states in the stable status of Markov Chain, multi-hop reliability performance for 1-D, 2-D networks with node location information, and upper bound and lower bound of multi-hop reliability for networks without location information were derived. Simulation and experiments were carried out, which validated our analysis. Since the dynamic link model is flexible, this framework can be used to predict multi-hop reliability of receiver contention-based protocol in dynamic networks with more complex link models. For future work,

recovery and retransmission scheme will be investigated to enhance the hop by hop communication reliability.

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APPENDIX

The derivation of $w(i, j)$. If the transmitter is at id , only the sensors in its forwarding zone can act as the relay. The probability that the advancement will lead to a node in Δ_{i-j} is expressed as:

$$w(i, j) = \left(1 - \overline{r(j)}\right) \cdot \prod_{k=j+1}^{\min(Rv, i)} \overline{r(k)} \quad (18)$$

where $\overline{r(j)}$ is the probability that all the sensors in Δ_{i-j} can not receive the packet from the transmitter. In fact, going from id to a point in Δ_{i-j} corresponds to have no relays with process $\gamma > jd$, but at least one relay with process $\gamma > (j-1)d$. The probability that there are n sensors in Δ_{i-j} , can be calculated as:

$$c(n) = \frac{(-\rho s(j))^n}{n!} \exp(-\rho s(j)) \quad (19)$$

Where $s(j)$ is the area of Δ_{i-j} .

We denote $\overline{f_j(n)}$ the probability that these n sensors in Δ_{i-j} can not receive the packet. Exploring all the possible values of n , the probability that all the sensors in Δ_{i-j} can not receive the packet from the transmitter can be calculated with the total probability formula:

Whether a node in Δ_{i-j} can receive the packet from the transmitter is determined by the channel model Eqn. 1. We suppose it is independent with each other. If there are n sensors in Δ_{i-j} , we denote x_j the mean distance from these nodes to the transmitter. The probability that all these n sensors fail to receive the packet can be formulated as:

$$\overline{f_j(n)} = \prod_{m=1}^n (1 - Pr r(x_j)) \quad (20)$$

Substituting Eqn. 24 and Eqn. 26 into Eqn. 25, and then substitute Eqn. 25 into Eqn. 23, the transitional probability from id to a point in Δ_{i-j} can be calculated.