

# Priority-Based Receiver-Side Relay Election in Wireless Ad Hoc Sensor Networks\*

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## ABSTRACT

Receiver-side relay election has been recently proposed as an alternative to transmitter-side relay selection in wireless ad hoc networks. In this paper we study different prioritization schemes among potential relay nodes to achieve a better delay and contention resolution performance. We consider a priority criteria based on least remaining distance to the destination and propose a generalized mapping function to introduce relative priority among the eligible relay nodes. We show that, a suitable mapping can be found to achieve an optimum relay election performance, which also outperforms the random forwarding approach. Our intuition is guided by an analytic framework and verified by network simulation.

**Categories and Subject Descriptors:** C.2.1 [Network Architecture and Design]: Wireless Communication; C.2.2 [Network Protocols]: Routing Protocols

**General Terms:** Performance, Algorithms, Theory

**Keywords:** Receiver-side relay election, priority forwarding, MAC contention, forwarding delay

## 1. INTRODUCTION

Various distributed forwarding schemes have been proposed for multihop wireless communication networks, where transmitting nodes select one of their neighbors to relay data packets toward the destination [1],[2]. In these schemes, simple criteria such as the relaying neighbor's geographical proximity to the transmitter or the final destination, or the energy required to transmit a packet are used by a transmitting node to select the best possible relaying neighbor. Such forwarding approaches require that a list of all local neighbors be maintained at a node. However, maintaining a local neighborhood list at all nodes in a dense network with dynamic network environment and making sure the selected relaying node is active (e.g., by wake up signals or

coordinated sleep patterns) may be costly for the resource constrained sensor nodes.

An alternative to transmitter-side relay selection is a forwarding scheme in which the transmitting nodes do not decide which one of their neighbors would relay their data packets, rather all relay candidates contend among themselves to relay the packets toward the final destination [3][4]. Ideally, to avoid packet duplication, only a single neighbor should be elected among all candidates as next hop relay. We will refer to this contention resolution process as *receiver-side relay election*. One essential advantage of receiver-side relay election is that a complex optimality criteria such as received signal strength or residual energy at candidate relays can be considered in a more efficient way which would have been infeasible or too costly in case of transmitter side relay selection.

Note that, because the relay election process is a distributed decision, multi-access collisions are likely to occur among two or more best relay candidates. When a collision happens, the election process fails, increasing the delay incurred to data packets. The effectiveness of receiver-side relay election process is best characterized firstly by the quality of the elected relay with respect to a chosen optimality criteria and secondly by the level of vulnerability of the election process to collisions. To elect a *good* relay node at the end of the contention resolution period, different optimality criteria, such as, maximizing per-hop progress toward the destination, minimizing per-node energy consumption, maximizing the end-to-end throughput, etc., can be used as a basis of prioritization among potential relays. In [3], one hop progress toward the final destination is used as the priority criteria. However, the authors considered no specific contention scheme in their routing performance analysis.

We observe that, while the receiver-side relay election approach could be a potential low-cost and distributed solution to energy optimized multihop wireless routing, a careful investigation on medium access control (MAC) contention resolution and the network performance is necessary to assess the end-to-end performance more accurately.

In this work, we study the MAC contention issues in different priority-based receiver-side relay election schemes and the associated per-hop delay performance. We focus on the performance of two main schemes, namely, *random forwarding*, *priority forwarding*, where the priority criteria is chosen based on the forwarding node's distance to the destination. We propose a generalized mapping function for the prioritization, in which the shape of relative scheduled time priority is governed by a mapping shape parameter. Through prob-

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\*This work has been supported in part by the NSF under Grant 0435250.

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IWCMC'06, July 3–6, 2006, Vancouver, British Columbia, Canada.  
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abilistic analysis, supported by simulations, we show that, in a given network setting, there exists a suitable shape parameter that offers an optimum relay election performance in terms of per-hop progress and effective delay in successful relay election process. The results could be used to introduce more complex decision criteria in relay election process, such as energy-awareness, power control, and mobility, to obtain an optimal network wide performance.

The rest of the paper is presented as follows. Related work on multihop relaying in wireless ad hoc networks is surveyed in Section 2. Section 3 describes the basics of receiver-side relay election and presents formal definitions of the prioritization schemes. The analytic framework for performance evaluation of the prioritization schemes is presented in Section 4. Analytic and simulation results are contained in Section 5. Concluding remarks are drawn in Section 6.

## 2. RELATED WORK

The question on *how* to select the next hop for optimum multihop communication has long been considered in packet radio networks [5],[1],[2],[6]. Many position-based forwarding solutions have been proposed which select as next hop the closest neighbor, or the neighbor closest to the destination [6][7]. Until recently, all position-related forwarding schemes proposed to make the selection of the next hop node at transmitter-side. These schemes may work well with lightly populated, and relatively static ad hoc networks. However more dynamic, dense, and resource constrained networks, such as sensor networks, require that we reconsider the question of *where* to make the next hop selection.

Recently a few researchers [3],[4] have independently considered forwarding schemes in which transmitting nodes do not need to select the next hop. Rather, all eligible candidates compete among themselves to relay the packets. While [3] considered remaining distance to the destination based forwarding node selection priority criteria, it did not capture the additional MAC contention in the election process. Rather, it was assumed on the one hand that somehow the best relay is always elected and on the other hand that the election process is always successful. [4] studied three possible variants of forwarding node election aiming at reduced packet duplication, where it was assumed that more than one nearly-simultaneous responses could be successful. Priority dependent MAC contention probability and the related delay in successful relay election process was not considered.

For receiver-based forwarding schemes to work certain networking conditions need to be ensured. Specifically, every node desiring to transmit should find with high probability at least one active neighbor in the forward direction to relay its packets. The feasibility and stability of such networks conditions have received some attention in the research community. [8] considered a network of independent Bernoulli type nodes and derived the limiting probability that every node has at least one active neighbor in highly dense networks. [9] also considered the feasibility of a network of sensor nodes with independent asynchronous duty-cycles in which transmitting nodes can simply broadcast their packets and have them relayed by available active neighbors. However, because the main focus of the authors is robustness, the approach does not discourage packet duplication and may not be optimal in dense networks.

## 3. RECEIVER-SIDE RELAY ELECTION

We consider a network of uniformly random distributed nodes with homogeneous and circular coverage, and independent and asynchronous sleeping behavior. It is assumed, similar to 802.11 distributed coordination function (DCF), RTS/CTS (request-to-send/clear-to-send) message exchange is done between the transmitter and a potential forwarder before the data packet forwarding. However, unlike in 802.11, the RTS message is broadcast to all local neighbors, and a forwarder's CTS response is suitably delayed to minimize the potential contention. It is also assumed that a node is aware of its geographic location or virtual (hop-count based [10]) location information of its own and the destination. In the following, we elaborate further the concepts of contention resolution, vulnerability of collision, and prioritization strategies in relation to receiver-side relay election.

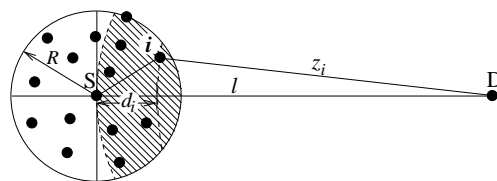
### 3.1 Contention Resolution

Hop-by-hop forwarding is generally done in packet radio networks based on a decision criteria to obtain desired nodal or network-wide performance objective. In receiver-side relay election, these decision criteria are (implicitly) used as priority measures in the distributed relay election. Before we analyze the performance of various prioritization schemes we first present the description of a basic election process using time delay as contention resolution.

A node desiring to send data packet first sends a broadcast RTS packet containing the optimality-criteria and location information of itself and the final destination. After receiving the RTS packet, every eligible relay candidate  $i$  (the shaded region in Fig. 1) schedules a reply time:

$$X_i = g(\Omega_i), \quad (1)$$

where  $\Omega_i$  is the quality measure of node  $i$  computed based on a given criterion used by the forwarding scheme.  $g(\cdot)$  is a mapping function that implements the prioritization of the election process and its nature determines the quality of the elected relaying neighbor with respect to the set of optimality criteria and the vulnerability of the election process to collision among two or more best candidates.



**Figure 1: Area of contention for packet forwarding.**  $R$  is the coverage range.  $i$  is a forwarding contender, which offers forward progress  $d_i$  towards  $D$ .

Next, every relay candidate  $i$  listens to the wireless medium between the time 0 and  $X_i$ . If no other CTS is received before time  $X_i$ , then node  $i$  considers itself the winner of the election process and sends a CTS packet with its signature to the transmitting node. If a node overhears a CTS transmission during its waiting period, it gives up the contention, assuming that a better forwarding candidate has been found.

### 3.2 Vulnerability to Collision

Because of the distributed nature, receiver-side relay election processes are vulnerable to collision. The election process fails to elect single next hop when two or more re-

lay candidates schedule the same or very close RTS reply times. Note that, this type of collision is different from (and additive to) regular medium access collision such as those caused by hidden or exposed terminals. Since all forwarding schemes, independently of whether the relay selection is done at the transmitter-side or at the receiver-side, are subject to the same regular medium collision, in this work we are not interested in quantifying this type of collision.

To quantify the collision in the election process, assume node  $j$  schedules reply time  $X_j = \min_i \{X_i\}$ . Collision happens if there exist a at least one node  $k$  ( $k \neq j$ ) such that

$$|X_j - X_k| \leq \beta, \quad (2)$$

where  $\beta$  is the collision vulnerability window, which may depend on the MAC scheme, nodes' clock precision, signal detection time, and receive-transmit changeover delay.

Upon correctly receiving a CTS packet, the transmitter sends the data packet to the forwarder. If the transmitter receives another correct CTS packet afterwards for the same data packet (if the earlier CTS packet was unheard by some nodes in the forwarding zone), it simply discards the CTS to avoid any packet duplication. In case of any CTS message collision, all forwarding nodes give up in that contention cycle, and, as in 802.11 DCF MAC contention resolution, we assume the transmitter re-initiates the election process by broadcasting another RTS packet after a timeout.

### 3.3 Prioritization types

We categorize prioritization functions into two main groups: *purely random* and *absolute priority-based*. Below, we present definitions of the two prioritization types, assuming, without loss of generality, that the desired objective is to maximize the decision criteria  $\Omega$ . For the sake of completeness, a variation of forwarding scheme, called *hybrid priority*, is also defined, which is derived from the combination of the priority-based approach and the random approach.

**DEFINITION 1.** *In **purely random** forwarding, no priority is given to better candidates during the election process. If nodes  $j$  and  $k$  are two relay candidates, then the fact that node  $k$  is a better candidate than node  $j$  ( $\Omega_j \leq \Omega_k$ ) does not increase the chances that  $k$  is elected over  $j$ . Formally,*

$$Pr[X_k \leq X_j | \Omega_j \leq \Omega_k] = Pr[X_k \leq X_j]$$

Note that in this case the decision criteria  $\Omega$  does not have any role in electing a relay.

**DEFINITION 2.** *In **absolute priority** forwarding, absolute priority is given to better candidates during the election process. If nodes  $j$  and  $k$  are two relay candidates, then the fact that  $k$  is a better candidate than  $j$  ( $\Omega_j \leq \Omega_k$ ) guarantees that  $k$  is elected over  $j$ . That is,*

$$Pr[X_k \leq X_j | \Omega_j \leq \Omega_k] = 1$$

Note that absolute priority can be obtained with a function  $g(\cdot)$  which is deterministic and monotonically decreasing with respect to  $\Omega$ .

**DEFINITION 3.** *A **hybrid priority** combines absolute priority and purely random selections, and gives priority but no guarantee to a better candidate in the election process. If nodes  $j$  and  $k$  are two relay candidates, then the fact  $k$  is a better candidate than  $j$  ( $\Omega_j \leq \Omega_k$ ) increases the chances but does not guarantee that  $k$  is elected over  $j$ . That is,*

$$Pr[X_k \leq X_j] < Pr[X_k \leq X_j | \Omega_j \leq \Omega_k] < 1$$

However, hybrid priority will not be discussed further in this paper; it will be left as a future research extension.

## 4. ANALYSIS OF PRIORITIZATION SCHEMES

We now determine the characteristics of the prioritization function  $g(\cdot)$  (see (1)) and analyze the priority-specific performance of relay election processes. We are particularly interested in characterizing the vulnerability to collisions and the effective delay in successful relay election process.

It is assumed that based on the location information and a set priority criteria in the RTS packet each node can have its own measure  $\Omega_i$  of forwarding decision.

Two main time delay based contention resolution criteria that we consider are random delay and prioritized delay. In case of random delay, a node in the forwarding zone picks up a random waiting time drawn from a given probability distribution function (pdf) before sending its CTS message. We consider uniformly random (`uni_rand`( $t_2, t_1$ )) distribution of chosen waiting time in the range  $[t_2, t_1]$ . The decision criteria  $\Omega$  in this case is independent of the nodes locations (as long as they are in the forwarding region (cf. Fig. 1)), and thus the waiting time  $X_i$  of node  $i$ , i.e., the mapping function  $g(\cdot)$ , is the corresponding random distribution itself.

On prioritized election process, there could be many possible criteria, namely, maximum residual energy based, receiver signal strength based, maximum per-hop progress based, etc., or a combination of them. In our study, we have chosen maximum per-hop progress toward the destination as the absolute priority criteria. Accordingly,  $\Omega_i$  represents the progress toward the destination  $d_i$  a relay candidate  $i$  can offer, if elected (cf. Fig. 1). In this case, the mapping function  $g(\Omega_i)$ , which is monotonically decreasing with respect to  $d_i$ , can be expressed as

$$X_i = g(\Omega_i) = \{a(\alpha)d_i + b(\alpha)\}^{1/\alpha} \quad (3)$$

where the coefficients  $a(\alpha)$  and  $b(\alpha)$  are chosen such that the prioritized delay of a forwarding region node remains within  $[t_2, t_1]$ , as in the `uni_rand` case.  $\alpha$  is the shape parameter ( $\alpha \neq 0$ ) that governs the nature of relative priority of potential relay nodes.  $a(\alpha)$  and  $b(\alpha)$  are given by:

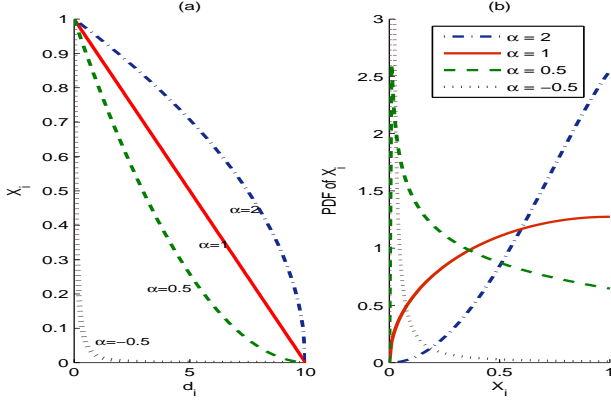
$$a(\alpha) = \frac{t_2^\alpha - t_1^\alpha}{R}; \quad b(\alpha) = t_1^\alpha \quad (4)$$

In Fig. 2 the priority-based mapping function  $g(\cdot)$  and the corresponding mapped random variable  $X_i$  (scheduled time of node  $i$ ) as a function of the shape parameter  $\alpha$  is depicted. It is interesting to observe that, by varying  $\alpha$ , relative priority of different node election can be achieved. For example,  $\alpha = 1$  corresponds to the linear mapping with respect to one-hop progress, whereas  $\alpha = -1$  corresponds to the inverse mapping. It is remained to be seen the effect of different mapping on the relay election delay and collision vulnerability, which will be discussed subsequently.

In the following development, we first derive the generic expressions for delay and collision probability. Specific cases of relay election strategies are taken up as examples.

### 4.1 Relay Election Delay

To find the time required to successfully elect a relay, denote by  $\{X_i\}_{i=1,2,\dots}$  the set of independent and identically distributed random variables representing the scheduled reply times of all eligible relay candidates. The number of



**Figure 2:** (a) Mapping functions in one-hop progress based absolute priority as a function of  $\alpha$ ; (b) corresponding pdf's of mapped random variable  $X_i$ .  $R = 10$ .

such contenders is itself another random variable  $C$ , which is Poisson distributed with parameter  $\lambda$ , the average number of active forward direction neighbors. The conditional duration of one election process is define as  $Y = \min_i \{X_i\}$ . We are interested in the distribution ( $f_Y(y)$  and  $F_Y(y)$ ) of  $Y$  for an arbitrary prioritization scheme, i.e., for arbitrary distribution ( $f_X(x)$  and  $F_X(x)$ ) of the  $X_i$ 's.

If we consider  $C = c$  active contending candidates, each with a scheduled time  $X_i$   $\{i = 1, 2, \dots, c\}$ , the conditional cumulative distribution function (cdf) of  $Y$  is obtained as

$$\begin{aligned} \Pr[Y \leq y | C = c] &= 1 - \Pr[Y > y | C = c] \\ &= 1 - \Pr[\min_i \{X_i\} > y] \\ &= 1 - \prod_{i=1}^c \Pr[X_i > y] \\ &= 1 - \{1 - F_x(y)\}^c \end{aligned}$$

Note that  $Y$  is defined only for  $c \geq 1$ . The unconditional cdf of  $Y$  can then be obtained by total probability:

$$\begin{aligned} \Pr[Y \leq y] &= \sum_{c=1}^{\infty} \Pr[Y \leq y | C = c] \frac{\Pr[C = c]}{\Pr[c \geq 1]} \\ &= \sum_{c=1}^{\infty} [1 - \{1 - F_x(y)\}^c] \frac{\lambda^c e^{-\lambda}}{1 - e^{-\lambda}} \end{aligned}$$

After simplification, we obtain

$$\begin{aligned} F_Y(y) &= \Pr[Y \leq y] = \frac{1 - e^{-\lambda F_X(y)}}{1 - e^{-\lambda}} \\ f_Y(y) &= \frac{\lambda f_X(y) e^{-\lambda F_X(y)}}{1 - e^{-\lambda}} \end{aligned} \quad (5)$$

Below, we apply the general result of (5) to two examples of prioritization.

#### 4.1.1 Uniformly Random Forwarding

Any forwarding solution in which all relay candidates contend by setting a purely random timer falls into this category. As an illustration, we consider the uniformly distributed random time between  $t_2$  and  $t_1$ , i.e.,

$$\begin{aligned} f_X^{rand}(x) &= \frac{1}{t_2 - t_1} \\ F_X^{rand}(x) &= \frac{x - t_2}{t_2 - t_1} \end{aligned}$$

Then, closed form expressions for the distributions with uniformly random  $X_i$  can be obtained from (5):

$$\begin{aligned} F_Y^{rand}(y) &= \frac{1 - e^{-\lambda \frac{y - t_2}{t_1 - t_2}}}{1 - e^{-\lambda}} \\ f_Y^{rand}(y) &= \frac{\lambda}{(t_1 - t_2)(1 - e^{-\lambda})} e^{-\lambda \frac{y - t_2}{t_1 - t_2}}. \end{aligned} \quad (6)$$

#### 4.1.2 Absolute Priority with Linear Mapping

For the absolute priority forwarding, we consider the case where scheduled time is a function of one-hop progress and linearly decreasing between  $t_1$  and  $t_2$ . Then, from (3)-(4), setting  $\alpha = 1$ ,  $X_i = \frac{t_2 - t_1}{R} d_i + t_1$ ,  $0 \leq d_i \leq R$ , where  $d_i$  is the forward progress to the destination of candidate relay  $i$  (cf. Fig. 1). The distribution of  $X_i$  can be deduced from the distribution of remaining distance [6], and can be approximately given by

$$f_{d_i}(d) = \frac{4(l-d)}{\pi R^2} \arccos\left(\frac{(l-d)^2 + l^2 - R^2}{2l(l-d)}\right) \quad (7)$$

The distributions of the scheduled time are given by

$$\begin{aligned} F_X^{lin}(x) &= 1 - F_{d_i}\left(\frac{t_1 - x}{t_1 - t_2} R\right) \\ f_X^{lin}(x) &= \frac{1}{|t_1 - t_2|} f_{d_i}\left(\frac{t_1 - x}{t_1 - t_2} R\right) \end{aligned} \quad (8)$$

From (6) and (8) the average delay in one relay election attempt can be obtained in these two cases. Delay results for these two examples along with the other variants will be presented in Section 5.

## 4.2 Election Failure Probability

As stated earlier (see (2)), the election process fails when the first two best candidates are not at least the collision vulnerability window apart from each other. Formally, denote  $Y$  as the minimum of the set of scheduled reply times:  $Y = \min_i \{X_i\}$ , and  $Y^*$  as the minimum of the remaining remaining nodes' scheduled reply times:  $Y^* = \min\{\{X_i\} - Y\}$ . Note that  $Y$  and  $Y^*$  can be considered identically distributed. Also, define  $S_Y(y) = 1 - F_Y(y)$  as the survival function of  $Y$ , and  $h(y) = \frac{f_Y(y)}{S_Y(y)}$ .

LEMMA 1. For a given collision vulnerability window  $\beta$ , the rate of failure of the election process is given by

$$P_{fail} = 1 - (h \odot S_Y)(\beta) \quad (9)$$

where  $\odot$  represents the correlation integral function defined by

$$(h \odot S_Y)(t) = \int_{-\infty}^{\infty} h(x) S_Y(t+x) dx$$

**Proof:** Under the condition  $Y = y$ , a collision occurs with the conditional probability  $\Pr[Y^* \leq y + \beta | Y = y] = \frac{F_Y(y+\beta) - F_Y(y)}{1 - F_Y(y)}$ . The unconditional probability of collision can then be obtained by

$$\begin{aligned} P_{fail} &= \int_{t_2}^{t_1} \Pr[y \leq Y \leq y + \beta] \frac{F_Y(y+\beta) - F_Y(y)}{1 - F_Y(y)} \\ &= \int_{t_2}^{t_1} f_Y(y) dy \frac{F_Y(y+\beta) - F_Y(y)}{1 - F_Y(y)} \\ &= \int_{t_2}^{t_1} f_Y(y) \frac{S_Y(y) - S_Y(y+\beta)}{S_Y(y)} dy \end{aligned}$$

After simplification, realizing that for  $y \geq t_1$ ,  $S_Y(y) = 0$ , and for  $y \leq t_2$ ,  $h(y) = 0$ , we have,

$$P_{fail} = 1 - \int_{t_2}^{t_1} h(y)S_Y(y + \beta)dy$$

and hence the proof.  $\square$

Failure probabilities for specific prioritization cases can be obtained from the respective distribution functions.

### 4.3 Effective Delay

With the knowledge of delay in one election attempt and the corresponding failure probability, t Because the distributed relay election process can fail due to collision, repeated attempts may be required for successfully finding a next hop. To have a baseline comparison of priority-specific approaches, one needs to compute the effective delay of an eventually successful relay election process. For this purpose, for simplicity we assume that in case of a collision of RTS reply message, the sender re-initiates another election process at the end of a fixed timeout window ( $t_1$ ), and repeats this process until a CTS is received successfully.\* The effective average delay before a relay is successfully found is given by

$$D_{eff} = \frac{P_{fail}}{1 - P_{fail}}t_1 + D, \quad (10)$$

where  $P_{fail}$  is the collision probability given in (9), and  $D$  the average delay is one attempt, obtained from (5).

Numerical and simulation results are shown below.

## 5. RESULTS

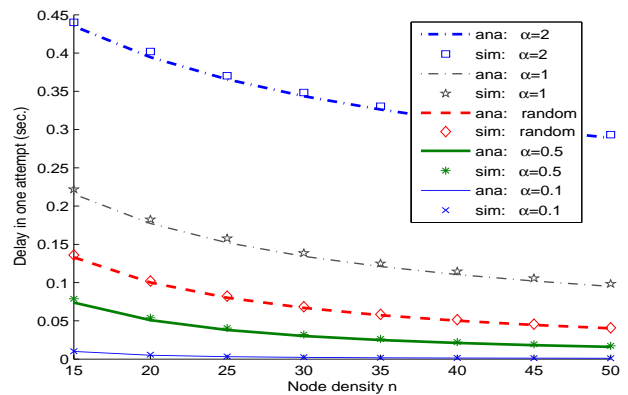
To evaluate the prioritization performance in receiver-side relay election process, we consider `uni_rand`( $t_2, t_1$ ) case and least remaining distance to the destination (LRD) based [6] priority forwarding forwarding, with the mapping function given in (3). The range of waiting time in both cases are set in  $[t_2, t_1]$ . The mapping parameter  $\alpha$  is varied to give different priority levels to different eligible nodes.

We assume independent and asynchronous sleep behavior of nodes in the network, which also gives different realization of set of active nodes eligible for forwarding in each transmission attempt by a sender. It is also assumed that the average number of active neighbors  $n$  of any node (also referred as node density) is stationary. For simplicity in obtaining the analytic results, average number  $\lambda$  of relay candidates of a node, denoted by the shaded region in Fig. 1, is approximated as  $\lambda = \frac{n}{2}$ .

All numerical and simulation results in this section are obtained with node transmission range  $R = 10$  and a sink node at a distance  $l = 100$  from the initial transmitting node. The collision vulnerability window is taken to be the changeover time of commonly available hardware ( $\beta = 250\mu s$ ). The scheduled reply times range from  $t_2 = 250\mu s$  to  $t_1 = 1s$ .

We first obtain the delay in one relay election attempt for different priority, where we are particularly interested in the behavior of the relative priorities controlled by the shape parameter  $\alpha$ . Fig. 3 shows that the smaller  $\alpha$ , the lesser the delay. This is because, as demonstrated in Fig. 2(b), for lower value of  $\alpha$  ( $< 1$ ) the the scheduled time distribution is

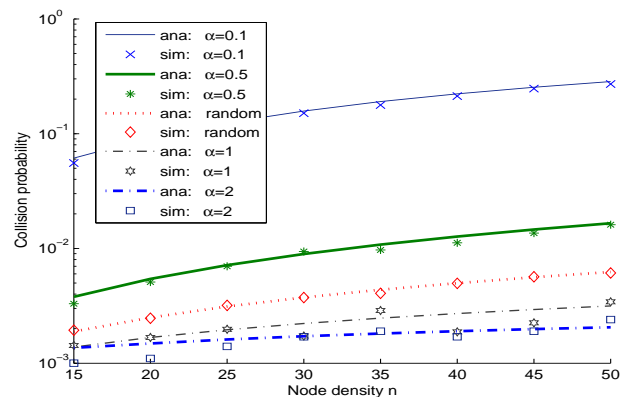
\*In practice, each transmission failure is followed by a binary exponential backoff, and only a finite number of re-attempts are done.



**Figure 3: Delay vs. node density in one relay election attempt in different priority approaches.**

squeezed toward the lower values. On the other hand,  $\alpha > 1$  stretches the distribution in the opposite direction, resulting in higher conditional delays.

The election failure probability  $P_{fail}$  plots in Fig. 4 show a reverse trend as  $\alpha$  changes. This is because at lower  $\alpha$ ,

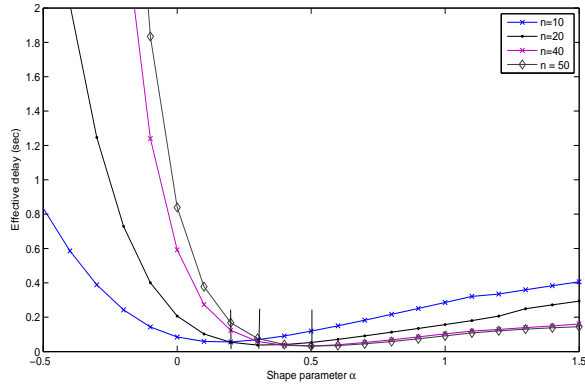


**Figure 4: Election failure probability  $P_{fail}$  vs. node density  $n$  in different priority approaches.**

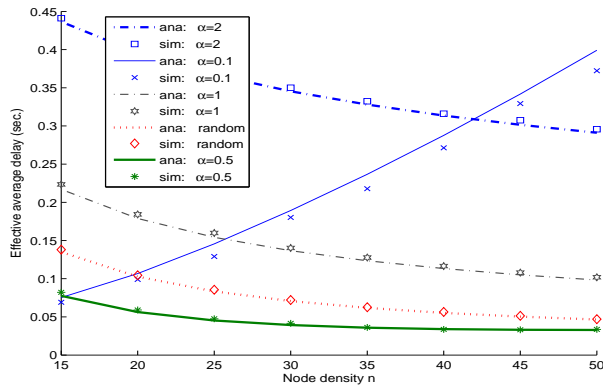
since the distribution of scheduled time is shifted toward the lower range, there is a high chance that two best nodes have nearly the same scheduled time (see (2)) for the CTS message, leading to a collision.

With the observation of counter-directional trends of delay in one election attempt and election failure probability for different shape parameters, we first compute via analysis the effective delay performance in a successful relay election process. In Fig. 5 we show the effect of the shape parameter on the effective delay. We observe that an optimum shape parameter can be obtained to achieve the best tradeoff between delay and collision probability, which is also a slowly varying function of the node density. For example, at node density  $n = 20$ , the optimum shape parameter  $\alpha_{opt} = 0.3$  and the effective delay is nearly 37.9 ms, whereas, at  $n = 20$ ,  $\alpha_{opt} = 0.5$  and the effective delay is nearly 31.5 ms.

Next we obtain the effective delay in successfully electing a relay for different prioritization schemes. The intuition from Fig. 5 is verified in Fig. 6 via analysis and simulation that there is a critical value of shape parameter for which



**Figure 5: Analytically obtained effective delay vs. shape parameter and with node density  $n$  as parameter.**



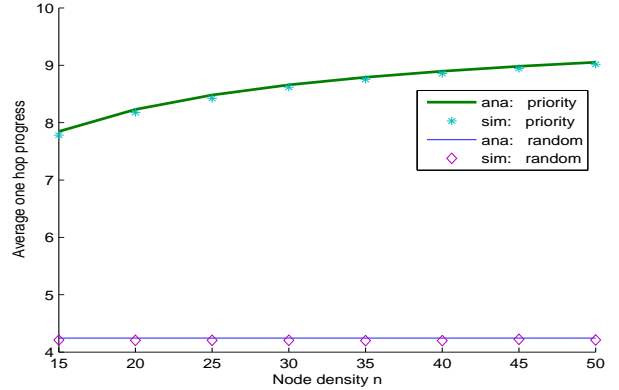
**Figure 6: Effective delay in successfully electing a relay vs. node density in different priority cases.**

an optimum election performance can be achieved. It is also observed that unless the prioritization scheme is suitably optimized, its performance can be even poorer than the random election process.

Node that the average one-hop progress in LRD based absolute priority forwarding is independent of the shape parameter as the best relay is elected in all cases. We observed that the average progress in random forwarding is nearly less than half of that in LRD approach (see Fig. 7). Although random forwarding has a reasonably good delay performance, which can be even better than the LRD based priority unless the shape parameter is chosen judiciously, very poor one-hop progress makes the random forwarding a rather less promising approach.

## 6. CONCLUSION

We studied receiver-side relay election priority schemes, where random forwarding and least remaining distance to the destination (LRD) based absolute priority were considered. A generalized mapping function for LRD based priority was proposed, where the mapping shape parameter can control the relative priority of eligible nodes as desired. Via probabilistic analysis, supported by network simulations, performance of different priority schemes were compared in terms of delay in one election attempt, elec-



**Figure 7: One-hop progress in random forwarding and LRD priority based approaches vs. node density, for any shape parameter  $\alpha$ .**

tion failure probability, and eventually, effective delay in a successful relay election process.

While random forwarding is simple and offers reasonably good delay performance, its drawback is poor one-hop progress. In case of LRD based priority, the shape parameter controls the delay and collision probability. Although a higher value of shape parameter offers lower delay in one election attempt, it has higher failure probability. It was shown that for a given network parameter, an optimum mapping function can be obtained (with an appropriate shape parameter) that offers the best tradeoff between delay and collision probability, which is also superior to the random forwarding with respect to effective delay as well as one-hop progress.

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