A Multi-Criteria Receiver-Side Relay Election Approach in Wireless Ad Hoc Networks

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Abstract—**Traditional purely greedy forwarding in wireless ad hoc networks is not optimal in most practical settings where *perfect-reception-within-range* cannot be assumed. Although a few link-aware routing schemes have been reported, the tradeoffs between greediness and link quality have not been studied. In this paper, we take a multi-criteria based receiver-side relay election approach in wireless multi-hop forwarding, where a single optimal node is elected among many candidates to relay packets toward the final destination. We introduce a general cost metric in the form of a multi-parameter mapping function, that aggregates all decision criteria into a single *virtual criterion* to rank potential relay candidates. We show that a suitable mapping function can be found, which trades off greediness for link quality to obtain optimal end-to-end network performance. Compared with the previously reported link-aware forwarding schemes, our results show a better energy performance and a substantial improvement in end-to-end delay.**

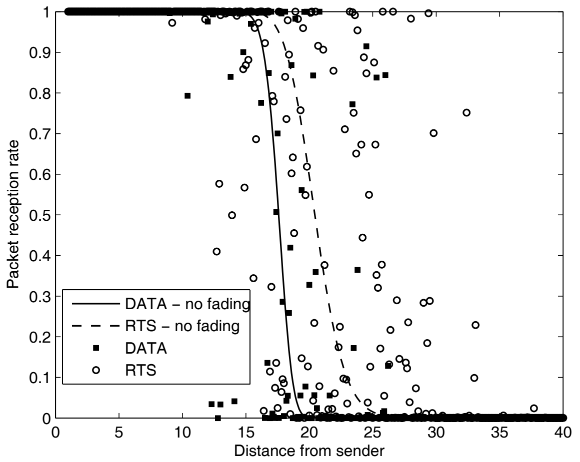

Fig. 1. Sample of reachability in realistic wireless settings.

I. INTRODUCTION

Various distributed forwarding schemes have been proposed for multi-hop wireless networks, where a transmitting node selects one of its neighbors to relay data packets toward the destination. In these schemes, a simple criteria, such as the relaying neighbor's geographical proximity to the final destination or the energy required to transmit a packet, is used by a transmitting node to select the best possible relay. Such forwarding approaches require that a list of all local neighbors be maintained at each node. However, maintaining a local neighborhood information 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 nodes.

Moreover, vast majority of the proposed rules for selecting the next forwarding neighbor assume unit disk coverage wherein a node within the coverage range is considered perfectly reachable, and they use only a single metric (e.g., one-hop progress, remaining energy) to choose the best candidate. However, in reality, the unit disk assumption does not hold good from physical layer perspective (for example, see Fig. 1), and a single criteria based forwarding node selection may not achieve the goal of network-wide optimal performance. As an example, the hop-count based greedy geographic forwarding approach [1], [2], [3] has received a great deal of attention in the ad hoc networking research community. In this approach, a transmitter tends to select node with poor link quality. For this reason, there have been a growing acceptance that the traditional purely greedy forwarding approach is not optimal in most practical settings where the unit disk assumption or a *perfect-reception-within-range* does not hold good [4]. Although some link-aware routing schemes have been reported recently [4], [5], [6], the tradeoffs between greediness and link quality have not been thoroughly studied.

The challenge in considering more than one criteria (such as link quality, delay, remaining energy) for the next hop selection lies in deciding the optimality of a particular neighbor with respect to other nodes, because different criteria could have possibly conflicting goals. In other words, the familiar scalar notion of optimality does not hold when multiple criteria are considered. However, even in a single optimality criterion based forwarding (e.g., one-hop progress), the receiver-side relay election introduces additional challenge of vulnerability to collision because of the distributed nature of the election process.

Furthermore, although the *transmitter-side relay selection* has the convenience of 'centralized' decision making, a transmitter has the additional burden of gathering and maintaining neighborhood information. An alternative to transmitter-side relay selection is *receiver-side relay election*, in which the transmitting node does not decide of the next hop relaying neighbor. Rather, all neighbors contend among themselves to elect the best possible relay [2], [7], [8]. With receiver-side relay election scheme, information on priority criteria, such as received signal strength, remaining energy, are readily available at each potential relay node, which can be easily included in deciding the next hop node.

In this paper, we consider the problem of multi-criteria receiver-side relay election in multi-hop wireless networks, where in each hop among many candidate relays one is elected to relay a packet toward the destination. We introduce a generalized multi-parameter mapping function that aggregates all decision criteria into a single *virtual criterion* to rank the potential relay candidates. We investigate optimal rules for next hop relay as applicable to both transmitter-side selection and receiver-side election based forwarding schemes. Beyond the theoretical formulation of the generalized multi-criteria based optimum election, as a demonstrative example of network performance evaluation, we consider the network performance based on two optimality criteria, namely one-hop progress (greediness) and packet success rate (link quality). We show that a suitable mapping function can be found which trades off the greediness for link quality and outperforms the reported transmitter-side link-aware forwarding schemes. Compared to the other schemes, our distributed two-criteria optimization results show a substantially better end-to-end delay performance and a reduction of up to 4 times in end-to-end packet loss for the same required energy.

The rest of the paper is presented as follows. Related works are surveyed in Section II. In Section III, the basic receiver-side relay election approach is outlined. Section IV introduces the multi-criteria receiver-side relay election and presents a general analytic framework for performance evaluation of the relaying schemes. A demonstrative example of two-criteria based relay election priority is also presented here. Analytic and simulation results on two-criteria based relay election are contained in Section V. Concluding remarks are drawn in Section VI.

II. RELATED WORK

The rules for optimum multi-hop communication has long been considered in packet radio networks [9], [1], [10], [3]. Many location-based forwarding solutions have been proposed which select as next hop the closest neighbor, or the neighbor closest to the destination [11], [3]. Until recently, all location-aware 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, have prompted reconsideration of the rules of multi-hop forwarding.

[2], [7] have independently considered forwarding schemes in which the next forwarding neighbor is elected among all potential relay neighbors in a distributed manner. [2] introduced Geographic Random Forwarding in which the next relaying neighbor is randomly selected from within a zone of contention. In this approach, to allow efficient multi-hop communication the contention area is divided into annular zones with priority given to zones most closest to the final destination. [7] introduced distance-dependent back-off as contention resolution mechanism and 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. Based on a single optimization criteria it was studied in [8] that near-simultaneous responses cause collision and possible failure of a relay election attempt. By introducing a parametric time back-off, it was shown that a suitable parameter can be chosen to optimize election time delay and mitigate vulnerability to collision simultaneously. All the above approaches were based on unit disk assumption of nodal coverage.

In some recent performance studies on ad hoc networks, link quality has been taken into account along with the progress toward the destination to choose an optimum forwarding node. In [4], a simple product form of packet success probability and progress toward the destination was considered, and an optimum node was selected that offers the maximum value of the product. The selection of next hop in [5] was based on a normalized advance (NADV) using different link costs (packet error rate, energy, delay) as normalizing factor. When packet error rate is considered along with progress to the destination, NADV is also equivalent to the product form as in [5]. Likewise, in [6] the same cost metric was applied in distance dependent loss aware geographic multi-hop relaying.

In this paper we show that the simple product form (*PROD*) can be outperformed by an optimum tradeoff between greediness and link quality. Additionally, our multi-criteria relaying framework can potentially accommodate any number of constraints in selecting/electing a next-hop node. As a specific example, we will consider greediness and reachability as two criteria for optimum relay election and will show that by judicious selection of weightage of different criteria a significantly improved network performance and nodal energy saving can be achieved.

III. RECEIVER-SIDE RELAY ELECTION FRAMEWORK

To motivate our generalized multi-criteria based analysis of relaying criteria, we first present a framework for receiver-side relay election based on a single criterion, where we will outline the concepts and the main results. For details, the reader is referred to [8]. In Section IV we will show that the multi-criteria case is amenable to a similar analysis by combining all criteria into one.

Receiver-side relay election is a decentralized process where the next relaying node is decided through contention among all potential candidates [2], [7], [8]. Similar to 802.11 distributed coordination function (DCF), a variant of 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, here the RTS packet is a broadcast massage containing position information of the sender and the final destination. Upon receiving this RTS packet, the potential relay candidates initiate a contention resolution process among themselves to elect the most suitable candidate as the next hop relay. The contention is typically resolved by introducing random or distance dependent time back-off. The first candidate to reply is the winner of the election process, and all other candidates abort.

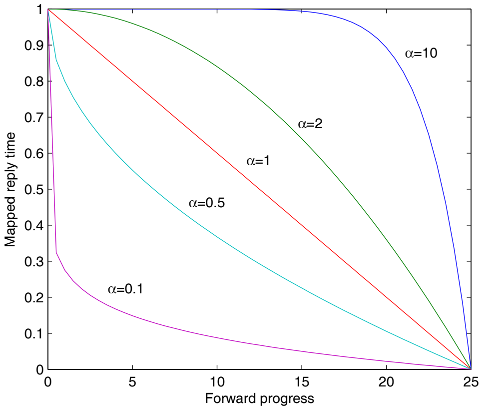

Fig. 2. Parametric single-criterion mapping functions. The forward progress interval [0,25] is mapped onto the time interval [0,1]

Let us introduce a family of function $g_\alpha(.)$ that map, for each candidate i, the single election criterion, forward progress d_i, onto the response time delay X_i.

$$X_i = g_\alpha(d_i) = a(\alpha){d_i}^{\alpha} + b(\alpha) \tag{1}$$

where α is a shape parameter used to tune the performance of the election process. Here we assume perfect reception within a range $[0, R]$ and the mapped time delay range is $[t_2, t_1]$. (1) is obtained by generalization of the linear mapping function (see Fig. 2). Coefficients $a(\alpha)$ and $b(\alpha)$ are obtained using the limiting conditions for the worst candidate ($g_\alpha(0) = t_1$) and the best candidate ($g_\alpha(R) = t_1$),

$$a(\alpha) = \frac{t_2 - t_1}{R^\alpha}; \quad b(\alpha) = t_1 \tag{2}$$

A. Election Delay

An important performance characteristic of a receiver-side relay election is the time duration of each election round. The average time until reception of a CTS response at the transmitter depends on the probability distribution of the mapped value X_i, which in turn is a function of the shape parameter α.

The cumulative distribution function F_x and density function f_x of the individual scheduled time X_i's are derived from the chosen the decision criterion (in this case, one-hop progress). Let $Y = \min_i \{X_i\}$ be the random variable denoting the time when the transmitter receives a CTS, in case the election process is successful. The distribution of Y is given by

$$\begin{aligned} F_Y(y) &= \Pr[Y \leq y] = \frac{1-e^{-nF_X(y)}}{1-e^{-n}} \\ f_Y(y) &= \frac{nf_X(y)e^{-nF_X(y)}}{1-e^{-n}} \end{aligned} \tag{3}$$

where n is the average number of active forward direction neighbors. From the above distributions the average delay of a contention process $E[Y]$ is computed.

B. Failure probability

Another characteristic of receiver-side election is the likelihood of collision between contending potential relays. Collisions are possible among two or more candidates if their respective back-off times are very close. Put mathematically, there could be collision and possible failure of the election process if candidates i and j schedule respective response time X_i and X_j such that $|X_i - X_j| \leq \beta$, where the collision vulnerability window β depends on the physical characteristics of the radio transceiver (e.g., transmit to receive switch-over time). The probability of collision can be expressed as [8]:

$$P_f = 1 - (h © S_Y)(\beta) \tag{4}$$

where © represents the correlation integral function defined by

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

$S_Y(y) = 1 - F_Y(y)$ is the survival function of Y, and $h(y) = \frac{f_Y(y)}{S_Y(y)}$ is the corresponding failure rate.

Although the average duration of the election process $E[Y]$ can be made arbitrarily small with small α, this also increases the probability of collision P_f during the election process. Considering the effective delay of a successful election process, an optimal shape parameter can be found that minimizes the duration of election rounds while mitigating the probability of collision. The value of the optimal shape parameter α depends on the recovery or retransmission policy used in case of collision during the election process. If the election rounds can be represented by unlimited Bernoulli trials until successful relay election, the optimal α value can be obtained by minimizing the effective delay D_e (see [8] for details), which is given by

$$D_e = \frac{P_f}{1 - P_f} t_1 + E[Y] \tag{5}$$

IV. MULTI-CRITERIA BASED RELAY ELECTION

A. *Optimality notion in the multi-criteria case*

As noted earlier, multi-hop forwarding based on the one-hop progress criterion can hardly be optimal because of the unreliable nature of wireless links and other nodal limitations, such as energy, buffer capacity, etc. However, as more than one decision parameters are considered, the ranking of an alternative candidate becomes less obvious than in the single criterion case. Consider for example Fig. 3 where two criteria are used to select the best relay node. With respect to a particular node (node A), the relationship with any other candidate can be classified as follows:

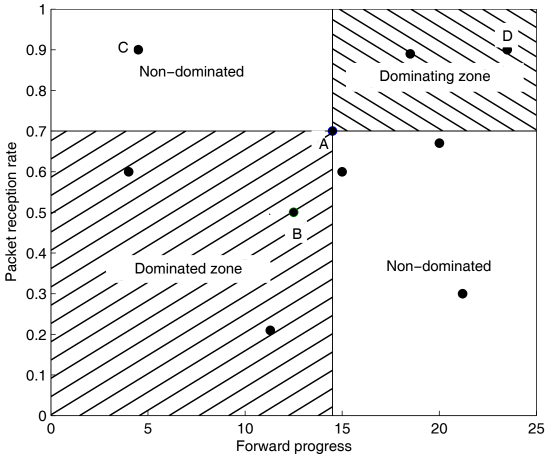

Fig. 3. Relation between a particular node (A) and other candidates. In general, only candidates in the hatched areas can be strictly compared with node A.

- All nodes in the *dominated zone* are clearly strictly 'inferior' compared to node A because they perform strictly poorer on at least one criterion and at most as good on all others.
- All nodes in the *dominating zone* are clearly strictly 'superior' compared to node A because they perform strictly better on at least one criterion and at least as good on all others.
- However, nodes in the two *non-dominated* zones perform better than node A on a single criterion and poorer on all others. Therefore nodes in the non-dominated zone cannot be qualified 'inferior' or 'superior' to node A.

Note that a forwarding decision can be made that maximizes all decision criteria whenever there exists a single candidate that dominates all others candidates (see node D in Fig. 3). However, in general, a single dominating candidate does not always exist and additional model is needed to define preference and tradeoffs among multiple criteria.

B. *Multi-criteria mapping function*

Now we introduce a general preference model in the form of an aggregating function that combines all criteria into a single virtual criterion used to out-rank all weak candidates.

Because the order induced by the dominance relationship on the set of alternative candidates is partial, there may exist among the set of alternatives, pairs of mutually incomparable candidates. With the mapping function, our objective is to introduce a single ranking scale through the use of an aggregating function that weights all criteria into a single one. Consider a decision based on k numerical criteria for which each candidate i has a performance index represented by the vector $\bar{\Omega}_i = (\Omega_{i1}, \Omega_{i2}, \cdots, \Omega_{ik})$. Without loss of generality, we assume that decision criterion (Ω_i) has a value in the range $[0, {\Omega_i}^{\max}]$ and has to be maximized.

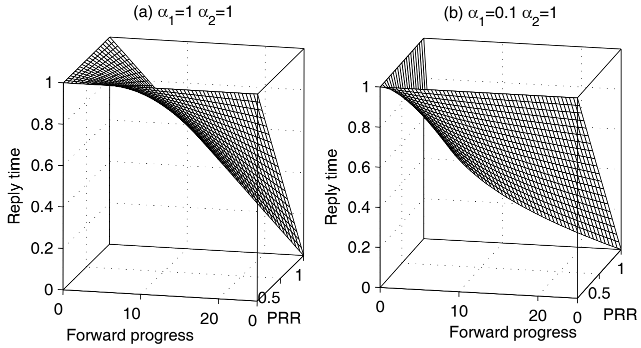

Fig. 4. Mapping function in a two criteria case.

We then map all decision variables onto the scheduled time by introducing the multidimensional family of function (see Fig. 4 for two criteria example).

$$g_{\bar{\alpha}}\left(\Omega_{i1}, \Omega_{i2}, \cdots, \Omega_{ik}\right) = a\left(\bar{\alpha}\right) \Omega_{i1}^{\alpha_1} \Omega_{i2}^{\alpha_2} \cdots \Omega_{ik}^{\alpha_k} + b\left(\bar{\alpha}\right) \tag{6}$$

where $\bar{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_k)$ is a k-parameter vector used to weight the k decision criteria. As in the single criterion case, the scheduled reply time for each candidate is $X_i = g_{\bar{\alpha}}\left(\bar{\Omega}_i\right)$.

From the perspective of transmitter-side relay selection, a corresponding cost metric can be derived from $g_{\bar{\alpha}}(.)$ as

$$C_{\bar{\alpha}}(\bar{\Omega}_i) = \Omega_{i1}^{\alpha_1} \Omega_{i2}^{\alpha_2} \cdots \Omega_{ik}^{\alpha_k} \tag{7}$$

Ranking all candidate with respect to $g_{\bar{\alpha}}$ (in descending order) or $C_{\bar{\alpha}}$ (in ascending order), creates a total ordering system on the set of all alternative candidates. That is, for any arbitrary two candidates i and j, $C_{\bar{\alpha}}(\bar{\Omega}_i) \leq C_{\bar{\alpha}}(\bar{\Omega}_j)$ or $C_{\bar{\alpha}}(\bar{\Omega}_i) \geq C_{\bar{\alpha}}(\bar{\Omega}_j)$.

Note that, for any positive real constant $m > 0$, $C_{m\bar{\alpha}}, m\bar{\alpha} = (m\alpha_1, m\alpha_2, \cdots, m\alpha_k)$ produces the same ranking as $C_{\bar{\alpha}}$. $g_{\bar{\alpha}}$ can therefore be seen as a single *virtual criterion* ($C_{\frac{1}{\alpha_1}\bar{\alpha}}$) which, as in single criterion case in Section III, we map onto the time interval $[t_2, t_1]$ for the purpose of receiver-side contention resolution:

$$g_{\bar{\alpha}}(\bar{\Omega}) = a(\bar{\alpha}) \left[C_{\frac{1}{\alpha_1}\bar{\alpha}}(\bar{\Omega}) \right]^{\alpha_1} + b(\bar{\alpha}) \tag{8}$$

Again, we obtain the parameter dependent coefficient from the limiting conditions for the worst and best candidates

$$a(\bar{\alpha}) = \frac{t_2 - t_1}{\Pi_1^k \left[\Omega_i^{\max}\right]^{\alpha_i}}; \quad b(\bar{\alpha}) = t_1 \tag{9}$$

As in the single criterion case, the multidimensional mapping function $g_{\bar{\alpha}}$ is a decreasing function with respect to each dimension considered individually.

C. Trading off greediness for link quality

With the general mapping function presented in the above, we now apply the multi-criteria mapping to an example case of forwarding scheme that finds an optimal tradeoff between link quality and greedy forward progress. An investigative approach is required because there is no a priori suggestion on what should be the optimal weights of the two criteria. For example, with $\alpha_1 = \alpha_2 = 1$, we obtain $C_{(1,1)} = d_x * p_x$ (the product of one-hop progress offered by node x and the corresponding packet success probability), which corresponds to the normalized advance (NADV [5]) and maximum expected progress (MEP [6]). However, as will be presented in Section V, our results show that this is suboptimal, and a substantially better network performance can be obtained by choosing appropriately the weighting parameters.

To see the impact of weight parameters (α_i) on the ranking of alternative relay candidates, consider node A (with $d_A = 14.5$ meter, $p_A = 0.7$) in Figs. 5. Note, how in case of $\alpha_1 = \alpha_2 = 1$ (Figs. 5(a)) a small increase in forward progress can compensate for a large decrease in link quality. On the other hand, with $\alpha_1 = 0.1$ and $\alpha_2 = 1$ (Figs. 5(b)), a node at almost 10 unit distance away from A could offer an almost equally good alternative relay.

Note also that, to find the rules for optimal forwarding decision making, only relative values of the two weight parameters are needed. In other words, we look for the ratio $\frac{\alpha_1}{\alpha_2} \triangleq \lambda$ which optimizes network performance metrics (e.g., energy, packet failure, and delay) both from the perspective of transmitter-side relay selection and receiver-side relay election. We will investigate the optimum value of λ via network simulations.

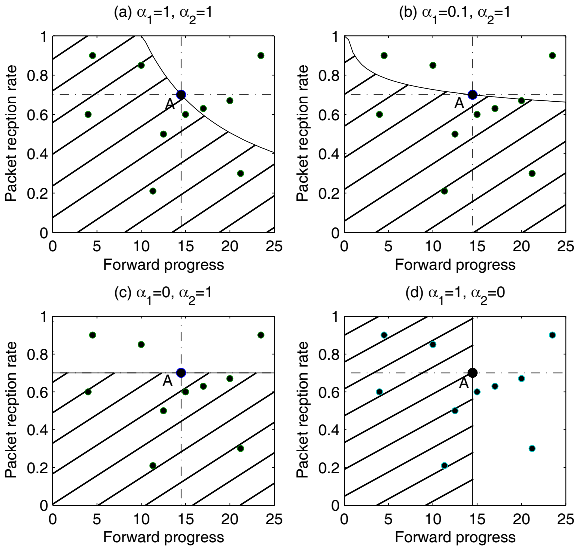

Fig. 5. Preference relation with respect to a particular node. The set of alternatives is partitioned according to weight given to each criterion.

V. Simulation and Results

We evaluate our multi-criteria decision optimization with a two-criteria example of greediness versus link quality.

A. Simulation model

We have considered randomly deployed nodes, with varied average density ρ (nodes/m^2). Nodal parameters have been based on Chipcon RFIC CC2420 operating with FSK modulation scheme at 900 MHz. All nodes transmit with a nominal power (0 dB) and at a rate of 19.2 kbps. Log-normal fading channel with standard deviation of channel disturbance 4 dB and path loss exponent 4.0 have been assumed. Fixed path loss has been calculated considering near field distance 1 meter. Network performance has been studied with approximate end-to-end distance 100 meter. The scheduled reply times range from $t_2 = 250$ msec to $t_1 = 1$ sec. Fixed packet size has been considered for all transmissions (50 Bytes for DATA and 4 Bytes for RTS). Each message is considered to have 100 data packets. No a priori transmission range has been assumed, all nodes capable of correctly receiving the initial broadcast RTS packet participate in the election process. Also, it has been assumed that a node is aware of the geographic location or virtual (hop-count based [12]) location information of its own and that of the destination. Each RTS packet contains position information of both the sender and the final destination.

B. *Performance Metrics*

B.1 End-to-end Packet Failure Rate

To measure the relaying performance with a given tradeoff parameter through an unreliable wireless medium, we consider packet failure rate along the route. As a baseline comparison, we record the number of transmissions required for successful delivery of a message at the final destination. Fig. 6 shows the packet loss rate with node density, which indicates that beyond certain high node density, irrespective of the tradeoff parameter, the loss performance stabilizes. This is because at very low node density a node tends to find a relay that is associated with a highly error-prone channel. As the density increases, an optimum tradeoff is possible.

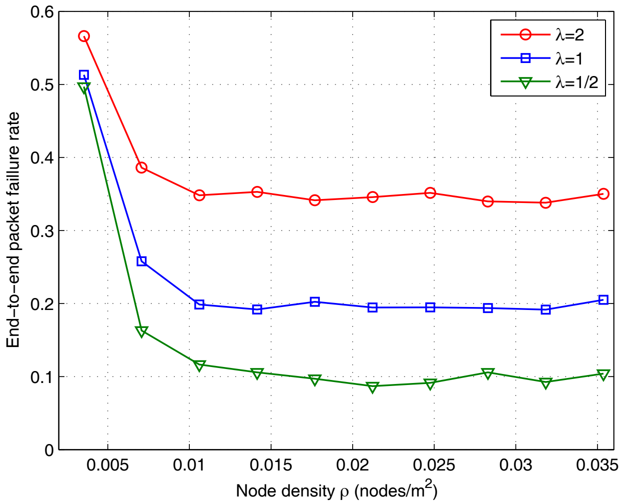

Fig. 6. End-to-end packet failure rate as function of density.

Fig. 7 shows that packet loss along the entire path can be reduced linearly with the tradeoff parameter λ. For example, $\lambda = \frac{1}{2}$ reduces the packet failure rate by 50% with respect to simple product of hop progress and packet success rate offered by a relay (i.e., with $\lambda = 1$).

B.2 End-to-end Forwarding Delay

We consider end-to-end delay due to packet transmission/retransmission. In our simulation, once a relay node is elected, up to `max_retx` retransmissions are allowed. More than `max_retx` packet failures result in link error and a new relay election process is initiated. Also each successful transmission takes t_{tx} amount of time and each retransmission causes an additional delay t_{out} due to timeout (negative acknowledgment). Fig. 8 presents end-to-end packet delay as function of node density which shows the effect of packet failure on packet delay (compare Fig. 8 with Fig. 6). Although Fig. 7 suggests that packet failure and, as a consequence, end-to-end delay can be made arbitrarily small by selecting smaller tradeoff parameter λ, our next result on energy efficiency shows that there exists a minimum value of λ beyond which adverse energy effect can be seen.

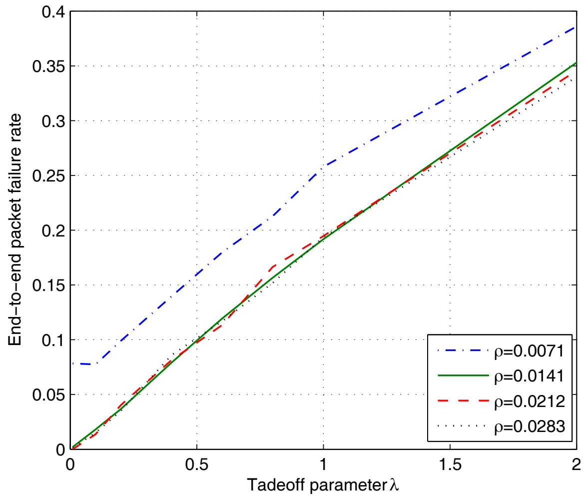

Fig. 7. End-to-end packet failure rate as function of the tradeoff parameter λ.

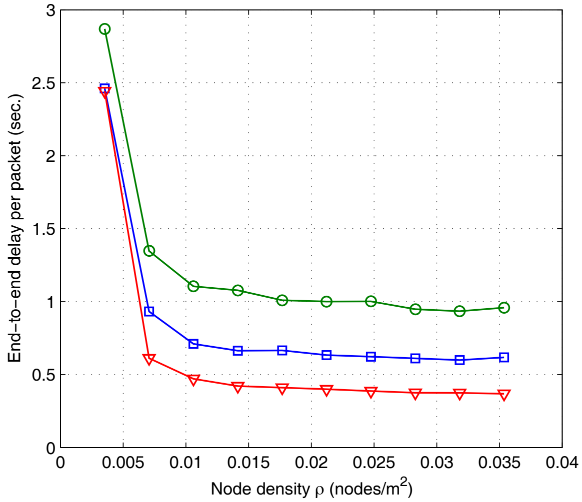

Fig. 8. End-to-end delay as function of node density. `max_retx` $= 8$, $t_{tx} = 21.1$ msec, $t_{out} = 84.4$ msec.

B.3 End-to-end energy consumption

We evaluate the energy efficiency of a given forwarding strategy by the number of transmissions required along the route for a successful end-to-end packet delivery. As expected, the energy requirement due to forwarding decreases with higher node densities, where it is more likely to find a neighbor offering a good combination of hop progress and link quality (see Fig. 9). Fig. 9 also shows that it is possible to improve energy efficiency by reducing the weight given to

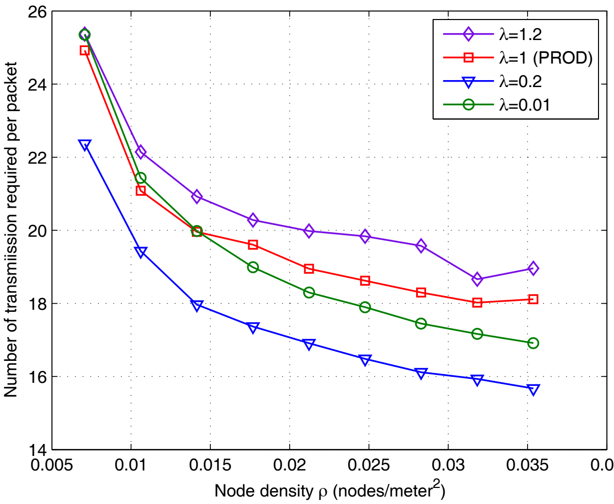

Fig. 9. Energy consumption (number of required transmission) for end-to-end packet delivery as a function of node density

hop progress. $\lambda = 0.2$ clearly outperforms the simple product form ($\lambda = 1$). It can also be seen that further reduction of the weight given to hop progress result in increasing energy consumption. Fig. 10 depicts that an optimal tradeoff between hop progress and link quality can be found that minimizes the required energy consumption. It shows that the optimal performance is achieved approximately at $\lambda = 0.2$. Notice from 7 that this optimal λ can achieve up to *approximately 4 times reduction* in packet failure rate with respect to the simple product form of hop progress and packet success rate (i.e., with $\lambda = 1$).

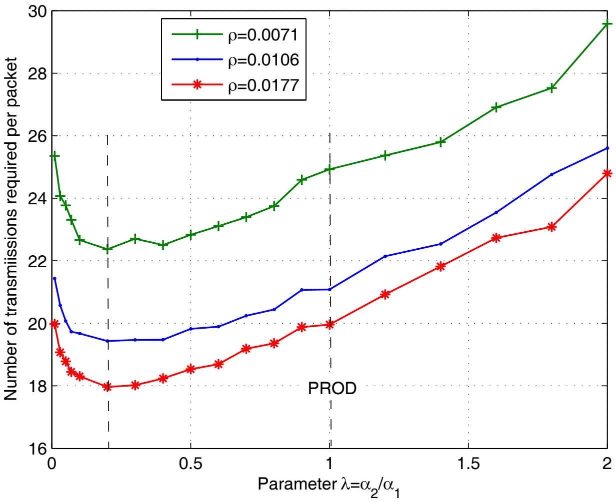

Fig. 10. Energy consumption (number of required transmission) as a function of the weightage parameter α_1 (with $\alpha_2 = 1$)

VI. CONCLUSION

We have presented a multi-criteria receiver-side relay election framework for multi-hop relaying in ad hoc networks. Via intuitive reasoning and examples we have first shown qualitatively the importance of finding optimum weighted relay election/selection criteria. A generalized cost metric in the form of multi-parameter mapping function has been proposed and used to investigate optimal tradeoff between greedy forwarding and link quality. As an illustrative example of two-criteria optimization, hop progress (greediness) and reachability (link quality) have been considered as the two parameters. It has been shown that a much better network performance in terms of total energy consumption for successful end-to-end routing can be achieved via judicious selection of the weighting parameter that optimally trades off between greediness and link quality. The multi-criteria mapping function is quite general and can also be applicable to transmitter-side relay selection process.

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