ON LINK LAYER POLICIES OF DATA FORWARDING OVER WIRELESS RELAYS

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ABSTRACT

For wireless/mobile ad hoc networks, researchers have developed many routing protocols. A typical problem setting is such that a packet of data is routed from a source to a destination without a prior knowledge of any existing route. To deal with unknown existing route, local flooding is required for each hop of the packet. Such an approach is appropriate for establishing a new route or forwarding infrequent data packets. However, for large volume data transmissions, the above approach is very inefficient. We believe that for many applications, mobile ad hoc networks must allow large volume data transmissions (in many separate packets) within a short period of time. For such applications, data forwarding policy should be based on a pre-established route. However, to combat random fluctuations of link qualities between nodes in dynamic environment, data forwarding policy should also exploit the spatial diversity of distributed nodes in a given route. It is from this perspective that we propose and analyze a one-to-many (1/M) data forwarding policy where each packet transmitted from a node is destined to multiple receiving nodes, and the node that receives the packet successfully and has the highest ranking becomes the next transmitting node. All nodes involved belong to a pre-established route, but the dynamic nature of each transmitting node of a packet makes the 1/M policy superior to the conventional one-to-one (1/1) policy for networks where transmission power dominates processing power.

1. INTRODUCTION

For wireless/mobile ad hoc networks, researchers have developed many routing protocols. A typical problem setting is such that a packet of data is routed from a source to a destination without a prior knowledge of any existing route. To deal with unknown existing route, local flooding is required for each hop of the packet. Examples of those protocols are available in [1, 2, 3, 4, 5, 6].

The above approach is appropriate for establishing a new route in an ad hoc network or forwarding infrequent data packets. However, for large volume data transmissions, the above approach is very inefficient. We believe that for many applications, mobile ad hoc networks must allow large volume data transmissions (in many separate packets) within a short period of time. This period of time may be short enough so that the relative network topology is basically unchanged although the link qualities between nodes may fluctuate frequently due to motions of nodes or dynamic interferences. For such applications, data forwarding policy should be based on a pre-established route. However, to combat random fluctuations of link qualities between nodes, data forwarding policy should also exploit the spatial diversity of distributed nodes in a given route. This idea was also previously presented in [7] and [8] where both transmitting and receiving diversities of distributed relays are explored. In this paper, we propose and analyze a one-to-many (1/M) data forwarding policy where each packet transmitted from a node is destined to multiple receiving nodes, and the node that receives the packet successfully and has the highest ranking becomes the next transmitting node. All nodes involved belong to a pre-established route. We will show that the dynamic nature of each transmitting node of a packet makes the 1/M policy superior to the conventional one-to-one (1/1) policy for networks where transmission power dominates processing power.

2. A ROUTE-GUIDED ONE-TO-MANY (1/M) FORWARDING POLICY

For a given route in a dynamic environment where link qualities between nodes change rapidly with respect to the transmission rate of packets, multiple nodes downstream from a transmitting node may have non-negligible chances to successfully receive a packet. For each hop of a packet, if we allow the farthest node with successful reception to forward the packet, we should expect the transmission delay between the source and the destination of a possibly long route to be significantly reduced. This is the basic idea of our 1/M policy.

More specifically, we set a window size W first. For each packet, the transmitting node broadcasts the data packet to the targeted W nodes downstream, and the farthest node with a successful packet capture in this window will be allowed to forward the packet. In the best scenario, the packet can reach W hops away from the transmitter in one forward attempt. But the average forward progress depends on the success probabilities of capturing the packet at the receiving nodes. Here, the choice of a suitable window size W is important because if W is too big, there could be too much power consumed just for signal process-

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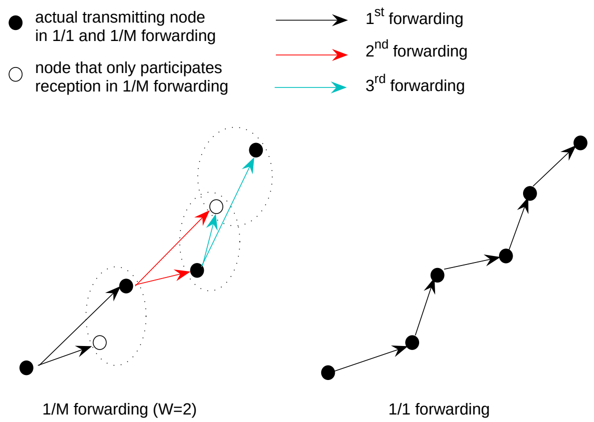

Figure 1. Comparison of the basic operation of 1/M forwarding policy and 1/1 policy

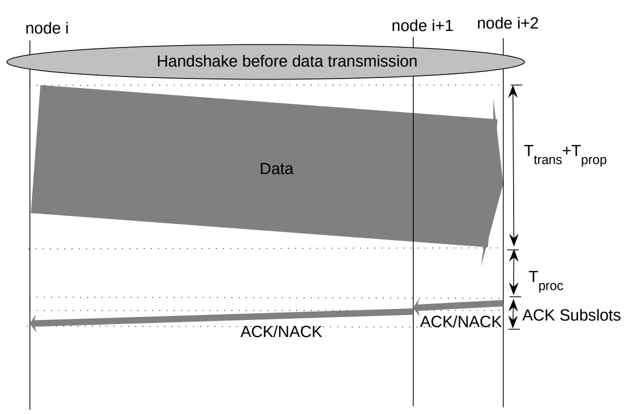

Figure 2. Illustration of the basic channel access in 1/M forwarding policy

ing at the receiving nodes (important for battery powered nodes), and the dialogue between the receiving nodes could consume even more transmission power as well as additional bandwidth or time. In practice, the transmission power by a transmitting node must have a proper upper bound so that there will be no excessive interference to neighboring routes.

In this paper, we will consider the simple choice: $W = 2$. As illustrated in Figure 1, for each hop of a packet, there is a transmitting node i and two receiving nodes $i+1$ and $i+2$ within the same route. With $W = 2$, the maximum gain of forward progress is thus bounded by two, but the cooperation among the receiving nodes $i+1$ and $i+2$ for the next forwarding can be quite simple as shown in Figure 2.

- Before transmitting a new packet from node i, a handshake in control channel (e.g., a request-to-send (RTS) and clear-to-send (CTS) mechanism) between node i and nodes $i+1$ and $i+2$ is established, and nodes $i+1$ and $i+2$ are ready for reception. Then, node i sends out one data packet.

- In the first sub-slot after data transmission, node $i+2$ sends back to node $i+1$ its acknowledgement (ACK) and prepares for the next forwarding if it has captured the packet. Otherwise, node $i+2$ sends a negative acknowledgement (NACK) packet to node $i+1$.

- Node $i+1$ keeps listening for ACK/NACK signal from node $i+2$ in the first sub-slot. If the feedback is ACK, node $i+1$ sends back an ACK to node i in the second sub-slot. If the feedback from node $i+2$ is NACK and node $i+1$ has captured the packet, an ACK is also sent from node $i+1$ to node i; or otherwise, a NACK is sent to node i.

- If node i receives an ACK from $i+1$ in the second sub-slot, the forwarding from node i was successful; or otherwise, a retransmission will be carried out in the next time slot.

We should note that the combination of this simple 1/M policy with Automatic Retransmission Request (ARQ) provides a spatial-temporal diversity, which enhances the transmission reliability. It is easy to verify that with $W = 2$, the two nearest transmitting nodes at any given time must be 5 hops apart to avoid self-interference. The required spacing between transmitting nodes can be achieved through a separate control channel. It is a reasonable assumption that the total bandwidth required for the control singling can and should be kept to be much smaller than that for data packet transmissions. Also note that for most radio ad hoc networks, the propagation time is generally much smaller than the packet length measured in time during transmission (which is a contrast against a typical broadband wired network). Such a packet length measured in time is also the transmission time. The total time slot required for each transmission of a packet should be no less than the sum of transmission time, propagation time, processing time, and ACK/NACK handshaking time.

3. PERFORMANCE ANALYSIS

3.1. A Capture Model for Packet Reception

Assuming a distance r between transmitter and receiver, the packet capture probability, with I interferers, can be modeled as [4]:

$$P_c(r, I) = \begin{cases} 1, & 10\log_{10} \frac{X(r)}{P_N + \sum_{i=1}^{I} X_i} \geq SINR_{min} \\ 0, & otherwise \end{cases} \tag{1}$$

where $X(r)$ is the instantaneous receiving power from the transmitting node to the receiving node given the distance r, which is assumed to be constant over a packet duration; X_i is the power from ith interfering nodes ($i = 1, ..., I$); $P_N = N_f N_0 BW$ is the noise power at the receiver, with N_f as the noise figure at the receiver, $N_0 = -173.8dBm$ (or $4.17 \times 10^{-21}J$) as the thermal noise power spectral density at room temperature, and BW representing the receiving bandwidth. For convenience of energy consumption estimation, we further define $P_{rad}(r_0)$ as the required radiated power given the required expected transmission range r_0.

Given $c := 10^{\frac{SNR_{min}(dB)}{10}}$, the capture probability for the given distance r between the transmitter and receiver is,

$$P_c(r) = E_I\{P_r[X(r) \geq c(P_N + \sum_{i=1}^{I} X_i)]\}. \quad (2)$$

Combining the large-scale fading (path loss) and the small-scale fading (Rayleigh distributed), the distribution of $X(r)$ is given by,

$$f(X|r) = \frac{1}{\mu(r)} e^{-\frac{X}{\mu(r)}}, \quad (3)$$

with $\mu(r) = P_{rad}(r_0)/[(\frac{4\pi d_0}{\lambda})^2(\frac{r}{d_0})^n]$. n is the path loss factor, λ is the carrier wavelength, d_0 is a reference distance.

3.2. Estimation of End-to-End (ETE) Delay, Energy Consumption and ETE Packet Loss Rate (PLR)

In this section, we first consider the packet transmission in a multi-hop route assuming no limit on the maximum number of retransmissions in ARQ. We assume that the network is stable during a session (no packet loss due to a permanent link breakage), and thus each packet eventually successfully reaches the destination. We will estimate the expected end-to-end (ETE) delay and energy cost for a successful transmission of packet from the source to the destination. Later on, we will consider the case that the maximum number of retransmissions of the ARQ strategy is bounded (i.e., called truncated ARQ). In this case, the ETE packet loss rate (PLR) P_{loss} is nonzero, and can be used to evaluate the network performance.

3.2.1. ETE Delay Estimation

For a packet transmission in a multi-hop route, the total delay of end-to-end transmission is the sum of all delays. The main delay components during a data packet forwarding attempt are packet transmission delay (T_{trans}), propagation delay (T_{prop}) and processing delay at receiver (T_{proc}). Accurate delay estimation is not a simple task, which depends on the actual (re)transmission strategy, channel model (error statistics), traffic model, error detecting/correcting code strategies, etc. In this paper, a simple delay estimation is used as shown next. First, we assume,

(1) a stop-and-wait (SW) ARQ scheme is used[1];

(2) the time interval for two consecutive (re)transmissions is defined as Δ (round-trip delay in ARQ)[2];

(3) errors on successive transmissions are independent;

(4) acknowledgement is error-free.

Based on the above assumptions, we can derive the expected delivery delay $D_{d,i}$. For the 1/1 policy, the success probability in a transmission attempt from the transmitting node in tier i ($i = 0, ..., M$) is given by $P^{11}_{succ,i} = P_c(r_{i,i+1})$. For the 1/M policy (with $W = 2$), we have

$$P^{1M}_{succ,i} = \begin{cases} 1 - [1 - P_c(r_{i,i+1})][1 - P_c(r_{i,i+2})] & i \neq M \\ P_c(r_{M,M+1}) & i = M \end{cases}, \quad (4)$$

where only the destination will be the receiver in the last hop ($i = M$) forwarding in the 1/M policy.

As the errors on all delivery attempts are independent, the delivery delay is a random variable with geometric distribution. Thus the expected delivery delay for a data packet from tier i to the next tier(s) is given by,

$$D_{d,i} = \frac{\Delta}{P_{succ,i}}. \quad (5)$$

Therefore, the expected ETE delay for a packet transmission in a route with $M + 1$ hops under 1/1 and 1/M policies can be estimated as [10],

$$D^{11} = \sum_{i=0}^{M} D_{d,i}, \quad (6)$$

$$D^{1M} = \sum_{i=0}^{M} D_{d,i} P^{1M}_{t,i}, \quad (7)$$

where, $P^{1M}_{t,i}$ is the probability that node i within the route will participate in the transmission of the given packet in 1/M policy, and for $W = 2$, it can be shown to be (see Appendix),

$$P^{1M}_{t,i} = 1 - \frac{P_c(r_{i-1,i+1})}{P^{1M}_{succ,i-1}} P^{1M}_{t,i-1} \quad i = 1, ..., M. \quad (8)$$

Since the source always participates in the transmission, we have $P^{1M}_{t,0} = 1$.

3.2.2. Energy Consumption Estimation

For a battery-powered relay, energy consumption is the paramount issue, i.e., it determines the lifetime of the route as well as the relay. For a forwarding attempt (successful or not), the energy consumed in transmitting and receiving nodes for one bit can be modeled as,

$$\begin{cases} E_{tx} = E_{c\_tx} + E_{amp} \\ E_{rx} = E_{c\_rx} \end{cases}, \quad (9)$$

where E_{c_tx}, E_{c_rx} is the energy consumed in transmitter and receiver electronics, respectively, and generally E_{c_rx} and E_{c_tx} are in the same order of magnitudes; $E_{amp} = \frac{P_{rad}(r_0)T_b}{G_{ant}\eta}$ is the energy dissipated in transmitter amplifier. Here, η is the power amplifier efficiency in the transmitter, G_{ant} is the antenna gain, and $P_{rad}(r_0)T_b$ is the transmitted energy for each bit from the transmitter antenna.

Therefore, we can define $E_{proc} := E_{c\_tx} + E_{c\_rx}$ as *processing energy*, which is energy consumption in a node's transceiver electronics; $E_{trans} := E_{amp}$ as *transmission energy*, which represents the energy consumption for radio transmission. Generally, there are two typical cases of energy consumption in wireless communications: (1) $E_{trans} >> E_{proc}$ where the required transmission energy is dominant (we call the network is *sparse* in

[1]Normally, the hop lengths in ad hoc networks are short (less than several hundred meters and hence $T_{prop} < 10\mu s$), and ACK/NACK packets are much shorter than data packets. Therefore, the delay due to propagation and acknowledgement is negligible, i.e., the round-trip delay is dominant by T_{trans} and T_{proc}, and hence a simple SW-ARQ scheme is a suitable choice.

[2]In a time slotted system, it is the duration of a time slot.

this case); (2) $E_{trans} \sim O(E_{proc})$ where E_{trans} is not significant - which is typical in short-range wireless communications, e.g., a wireless sensor [11]. In this case the network is called *dense*. Thus, We propose the metric E_{trans}/E_{proc} to represent the network's *sparseness*[3]. Note that the concept of *sparseness* here is from the nodes' point of view - if two nodes need cost much more energy for radiation than that for signal processing, the distance between them is considered as *long*; or otherwise the distance is *short*.

Similar to delay analysis, by considering the possibility of retransmissions, the average energy consumed for a packet with length of k bits in a successful forwarding from tier i $(i = 0, ..., M)$ to the next tier(s) for the 1/1 and 1/M policies is given by, respectively,

$$E_i^{11} = \frac{k(E_{tx} + E_{rx})}{P_{succ,i}^{11}}, \tag{10}$$

$$E_i^{1M} = \begin{cases} \frac{k(E_{tx}+WE_{rx})}{P_{succ,i}^{1M}} & i \neq M \\ \frac{k(E_{tx}+E_{rx})}{P_{succ,M}^{1M}} & i = M \end{cases}, \tag{11}$$

where for the 1/M policy, the nodes in the window ($W = 2$) participate in reception except the last hop, and W-fold reception energy is consumed. Here we assume that the energy cost for control signaling is negligible.

3.2.3. Estimation of End-to-End (ETE) Packet Loss Rate (PLR)

In practice, only finite delays and finite buffer size can be afforded, e.g. speech transportation [9], and hence the maximum number of retransmissions of ARQ strategy should be bounded, i.e., truncated ARQ. Generally, after maximal K times transmission attempts, if the receiving node can not capture the packet yet, the packet will be dropped. Therefore, ETE packet loss rate (PLR) P_{loss} is nonzero.

ETE PLR Estimation for the 1/1 policy: In this policy, the event that node i $(i = 1, ..., M)$ within a $(M + 1)$-hop route will participate in forwarding implies that all the nodes ($1 \sim i$) have successfully captured the packet within K transmission attempts allowed by truncated ARQ. Thus, the probability that a node will transmit is given by $P(0\ transmit) = 1$, $P(i\ transmit) = \prod_{j=1}^{i} \{1 - [1 - P_c(r_{j-1,j})]^K\}$, $i = 1, ..., M$. The ETE PLR for a route with $M + 1$ hops is,

$$P_{loss}^{11} = \sum_{i=0}^{M} [1 - P_c(r_{i,i+1})]^K P(i\ transmit). \tag{12}$$

There are two extreme cases - (1) $K = 1$, no ARQ strategy is used during forwarding, the ETE packet loss rate is $P_{loss}^{11} = 1 - \prod_{j=1}^{M+1} P_c(r_{j-1,j})$, i.e., unless all nodes within the route capture the packet (in one forwarding attempt), a packet loss happens; (2) $K \to \infty$, an ARQ (not truncated) is used, $P_{loss}^{11} \to 0$, i.e., each packet will be successfully received by the destination.

[3]Although E_{trans}/E_{proc} is determined by many system parameters of individual nodes, in a homogeneous network, it represents a critical characteristics of the network.

ETE PLR Estimation for the 1/M policy: In this policy, the event that node i $(i = 1, ..., M)$ within a $(M + 1)$-hop route will participate in forwarding also means all the nodes that participated in forwarding till i have successfully captured the packet. The probability that node i will participate in forwarding can be recursively calculated as,

$$\tilde{P}_{t,i}^{1M} = \tilde{P}_{i-2,i}\tilde{P}_{t,i-2}^{1M} + \tilde{P}_{i-1,i}\tilde{P}_{t,i-1}^{1M}, \quad i \geq 2, \tag{13}$$

and for $i = 1$, $\tilde{P}_{t,1}^{1M} = \tilde{P}_{0,1}\tilde{P}_{t,0}^{1M} = \tilde{P}_{0,1}$, where we use $\tilde{P}_{t,i}^{1M}$ to distinguish the probability $P_{t,i}^{1M}$ in the case of ARQ we defined in eqn.(8). $\tilde{P}_{i-2,i}, i = 2, ..., M$ is the probability that node i will be the transmitting node for the next forwarding given that the captured packet is from node $i - 2$; and $\tilde{P}_{i-1,i}$ is the probability that i will be the transmitting node for the next forwarding given that the captured packet is from $i - 1$. By defining $B(i,K) = \frac{1-(1-P_{succ,i}^{1M})^K}{P_{succ,i}^{1M}}$, it is not hard to show,

$$\tilde{P}_{i-2,i} = P_c(r_{i-2,i})B(i-2,K), \;\; i = 2, ..., M$$
$$\tilde{P}_{i-1,i} = P_c(r_{i-1,i})[1 - P_c(r_{i-1,i+1})]B(i-1,K), i = 1, ..., M.$$

When $K \to \infty$, we can see $\tilde{P}_{i-2,i} \to P_{i-2,i}$ and $\tilde{P}_{i-1,i} \to 1 - P_{i-1,i+1}$ in the case of ARQ (in Appendix eqn. (15)), $\tilde{P}_{t,i}^{1M} \to P_{t,i}^{1M}$ in eqn.(8). The ETE PLR for the 1/M policy in a route with $M + 1$ hops can be shown as,

$$P_{loss}^{1M} = \sum_{i=0}^{M} (1 - P_{succ,i}^{1M})^K \tilde{P}_{t,i}^{1M}, \tag{14}$$

where $(1 - P_{succ,i}^{1M})^K$ is the probability that node i fails to forward the packet in K attempts. When $K \to \infty$, an ARQ (not truncated) is used, $P_{loss}^{1M} \to 0$.

4. NUMERICAL RESULTS

In this section, we compare the performance of the 1/1 policy and the 1/M policy discussed in the last section. For simple illustration, we will focus on the comparison for a line relay network. Numerical results for random networks are available in [10]. Assuming that M relays have been deployed along the line from a source node to a destination node with the total distance d. All nodes are equipped with omnidirectional antennas and use the same radiation power for transmission. Two route structures are considered: (1) *Linear Relays (LR)*: all relays are deployed serially along a line with a constant adjacent distance $\frac{d}{M+1}$; (2) *Clustered Relays (CR)*: every N relays are clustered and all clusters (assuming $M = (L-1)N$, $L-1$ relay clusters) are deployed serially along a line with an equally separated distance $\frac{d}{L}$, where the distances between nodes within a cluster is much smaller than the distance between clusters . For these two strategies, the 1/M forwarding and the 1/1 forwarding will be used respectively to form four possible routing-forwarding schemes: (1) Linear Relays with 1/1 forwarding (LR-11); (2) Linear Relays with 1/M forwarding (LR-1M); (3) Clustered Relays with 1/1 forwarding (CR-11); (4) Clustered Relays with 1/M forwarding (CR-1M). We further assume that there is no self interference within the route.

Table 1. Example Transceiver Parameters [12]

Parameters	Values
SNR_{min}	10 dB (c=10)
Amplifier efficiency η	20%
Receiver noise figure N_f	11 dB (12.589)
Data transmission rate R	250 kbps
Carrier wavelength λ	0.125 m
Transmission Antenna Gain G_{ant}	-20 dBi (0.01)
Energy cost in transmitter electronics E_{c_tx}	14.52 nJ/bit
Energy cost in receiver electronics E_{c_rx}	44.52 nJ/bit

A practical transceiver example provided by Motorola Labs [12] is considered, and its parameters are listed in Table 1. A path loss factor $n = 3$ is used. We further set data packet size to $k = 1000$ bits, the distance between the source and destination to $d = 1000m$, the reference distance to $d_0 = 0.1m$. We assume 100 relays ($M = 100$) deployed between the source and the destination, and the time slot $\Delta = 8ms$, where $T_{trans} = 4ms$ and $T_{prop} < 1\ \mu s$.

We begin our investigation in the case of no constraint on the number of retransmissions, i.e., $K \to \infty$, focusing on the tradeoffs between ETE delay and energy. In the final subsection, we consider a finite K (truncated ARQ) and evaluate the ETE packet loss rates (PLR) in the 1/1 and 1/M policies.

4.1. ETE Delay

Figure 3 shows the ETE delays for different schemes as a function of transmission power P_{rad} in the unit of dBm. As expected, the ETE delays with the 1/M policy are uniformly better than the 1/1 policy. When $P_{rad} < 0$dBm, the improvement of ETE delay increases as P_{rad} increases. This is because a higher transmission power implies a higher average reception SNR and thus the a higher capture probability for the receiving node(s). But with further increase of the power beyond 0dBm, the delay improvement is saturated (50 %) under the constraint of preset window size $W = 2$. Also, we notice that when transmission power is less than -9dBm, LR schemes outperform CR schemes because only the receiving node(s) very close to the transmitter has a non-negligible chance to capture the packet (the hop length in CR is twice of that in LR). With the increase of power, LR-1M and CR-11 finally achieve the same delay performance.

4.2. Progress Efficiency

ETE delay is improved by the 1/M policy with more receivers (more processing energy) in a forwarding attempt. When transmission energy is dominant, it is clear that the 1/M policy not only improves ETE delay but also saves energy (by reducing energy waste in retransmissions). But when processing energy in the transceiver electronics is non-negligible, there is a delay-energy tradeoff. Therefore, we define the metric *progress efficiency* $\gamma = \frac{d}{D_{ETE} \cdot E}$ to fairly compare the 1/1 and 1/M policies, where γ represents the forward progress (meter) with a unit cost of time (second) and energy (Joule).

Figure 4 shows the progress efficiencies for different schemes as a function of transmission power P_{rad}. When P_{rad} is low, the 1/1 policy has a slightly better progress efficiency than the 1/M policy. For example, when $P_{rad} < -14$dBm ($E_{trans}/E_{proc} < 1.5$), LR-11 outperforms LR-1M; while with the increase of P_{rad}, LR-1M achieves a better progress efficiency than LR-11. And we notice that the maximal progress efficiency achieved by LR-1M is significantly higher (> 40%) than that in LR-11, which implies that a suitable increase of transmission power in LR-1M will bring a large benefit to efficiency. A similar trend is shown for CR-11 and CR-1M schemes - but the gain of 1/M over 1/1 policy is less than that in LR strategy as CR strategy alone provides a significant reliability improvement (reception diversity) over LR strategy (due to its route structure) when $P_{rad} > -11$dBm, which is clear by comparing progress efficiencies for LR-11 and CR-11.

To further understand when the 1/M policy will outperform the 1/1 policy in progress efficiency, Figure 5 shows the minimum ratio E_{trans}/E_{proc} (network *sparseness*) required by the 1/M policy to beat the 1/1 policy as a function of the number of relays (M) in both LR and CR strategies. In each strategy, systems operating with a E_{trans}/E_{proc} above the corresponding curve favor the 1/M policy, while systems below the curve favor the 1/1 policy. For example, in the case of $M = 100$ we discussed above, when $E_{trans}/E_{proc} > 1.5$ ($P_{rad} > -14$dBm) in LR or $E_{trans}/E_{proc} > 8.4$ ($P_{rad} > -6.5$dBm) in CR, systems favor the 1/M policy.

4.3. ETE PLR in LR strategy with Truncated ARQ

For illustration, we focus on the ETE PLR in LR strategy, the results can be easily extended to CR strategy. Figure 6 shows the ETE PLR in LR-11 and LR-1M as a function of transmission power P_{rad} given the maximum number of transmissions $K = \{2, 5, 10\}$. As expected, ETE PLR for both schemes decrease with the increase of P_{rad} (increase of SNR). Comparing 1/1 and 1/M policies, we find there is a significant transmission power saving by using 1/M policy when there is a hard constraint on the maximum number of transmissions (K is small), e.g., when $K = 5$ and required $P_{loss} = 10^{-4}$, 1/M policy will save about 3dB transmission power than 1/1 policy and for $K = 2$, the power saving is more tremendous. With the increase of K, the improvement in ETE PLR by using 1/M decreases as we know both schemes will achieve a zero packet loss when $K \to \infty$. This big power saving in small K scenario is due to 1/M policy provides a spatial diversity to compensate the temporal diversity loss in truncated ARQ with small values of K, while 1/1 policy has no such spatial-temporal diversity advantage.

Meanwhile, we should not forget that the power saving in 1/M policy has a cost of increasing processing energy as one more receiver has been involved in each forwarding attempt. Figure 7 compares the ETE PLR in LR-11 and LR-1M as a function of total energy consumption in a forwarding attempt[4]. There is a clear "cross point" for the LR-11 and LR-1M curves in the cases of

[4] This is a relatively conservative comparison as energy consumption in a forwarding attempt does not accurately represent the actual energy consumption in forwarding because the improvement of P_{loss} in 1/M policy generally reduces the average number of retransmissions, thus save more energy.

$K = 5$ and $k = 10$. Above the cross points, LR-11 is more energy efficient; while below the points, 1/M policy shows a big energy gain. For example, in the case of $K = 5$, to achieve $P_{loss} = 10^{-6}$, LR-1M only costs 50% energy of LR-11 in a forwarding attempt.

5. CONCLUSIONS

In this paper, we have explored the concept of one-to-many (1/M) policy for data forwarding over a pre-established route where the link qualities between nodes fluctuate randomly due to many possible reasons. We have analyzed the end-to-end (ETE) delay, and ETE packet loss rate. We have found that the 1/M policy outperforms significantly the conventional one-to-one (1/1) forwarding policy when the transmission power dominates the processing power or equivalently when the network is relatively sparse. We believe that for large volume data transmissions over wireless/mobile ad hoc networks, a route-guided data forwarding policy (as opposed to on-demand routing oriented data forwarding) is essential. When there are dynamic environmental interferences, the 1/M forwarding policy as shown in this paper is highly desirable.

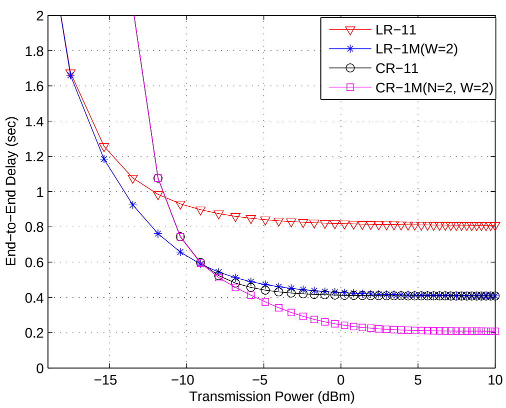

Figure 3. ETE delay for all schemes in consideration as a function of transmission power in an equidistant line network with $M = 100$ and source-destination distance $d = 1000m$

6. APPENDIX: PROOF FOR EQN. (8)

Let $P_{i-1,i+1}$ to be the probability that $i+1$ will be the transmitting node for the next forwarding given that the captured packet is from node $i-1$. Then, $1 - P_{i-1,i+1}$ is correspondingly the probability that i will be the transmitting node for the next forwarding given that the captured packet is from node $i-1$. We can show that,

$$P_{i-1,i+1} = \frac{P_c(r_{i-1,i+1})}{P^{1M}_{succ,i-1}}, \quad i = 1, ..., M. \tag{15}$$

On the other hand, the probability of node $i (i = 2, ..., M)$ participating in packet forwarding is only determined by the previous successful forwarding: (i) if node $i-2$ is the transmitting node in the previous forwarding and its forwarding is successfully received by node i, node i will be responsible for the next forwarding; (ii) if node $i-1$ is the transmitter in the previous forwarding

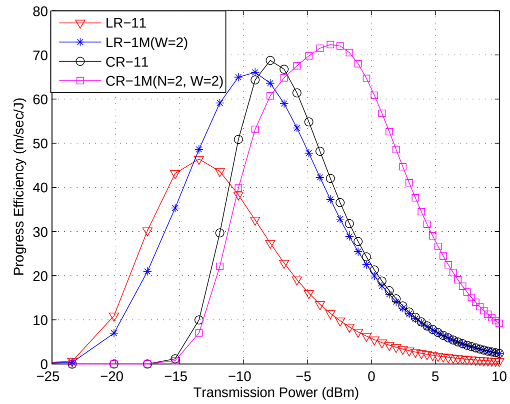

Figure 4. Progress efficiency for all schemes in consideration as a function of transmission power in an equidistant line network with $M = 100$ and source-destination distance $d = 1000m$

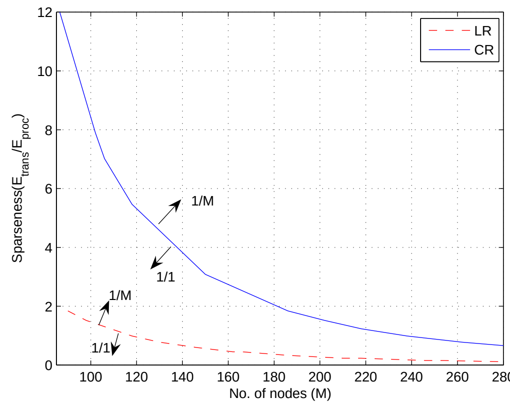

Figure 5. Minimum required *sparseness* E_{trans}/E_{proc} for 1/M policy to outperform 1/1 policy in both LR and CR strategies in an equidistant line network with M relays

and node $i+1$ does not capture the packet while node i does, node i will also be the transmitter for the following forwarding. Thus, we can calculate the transmission probability of node i for the given packet recursively as below:

$$P^{1M}_{t,i} = P_{i-2,i}P^{1M}_{t,i-2} + (1 - P_{i-1,i+1})P^{1M}_{t,i-1}, \tag{16}$$

and for $i = 1$, $P^{1M}_{t,1} = (1 - P_{0,2})P^{1M}_{t,0}$.

By using induction, we have,

(1) When $k = 1$,

$$P^{1M}_{t,1} = (1 - P_{0,2})P^{1M}_{t,0} = 1 - P_{0,2}P^{1M}_{t,0}, \tag{17}$$

where we use the fact $P^{1M}_{t,0} = 1$ as node 0 (source) always participates in forwarding.

(2) When $k = i (i \geq 1)$, we have,

$$P^{1M}_{t,i} = 1 - P_{i-1,i+1}P^{1M}_{t,i-1}. \tag{18}$$

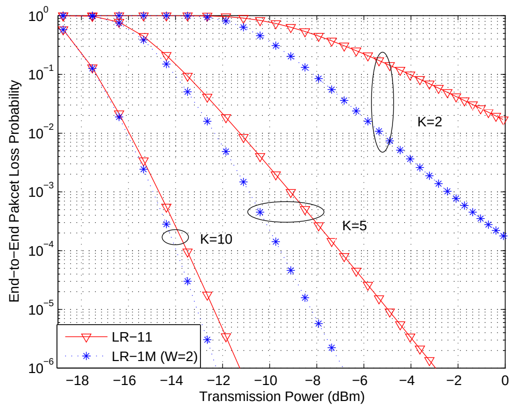

Figure 6. ETE packet loss rate for LR-11 and LR-1M schemes as a function of transmission power in an equidistant line network with the constraint on the maximum number of transmissions $K = \{2, 5, 10\}$ in truncated ARQ

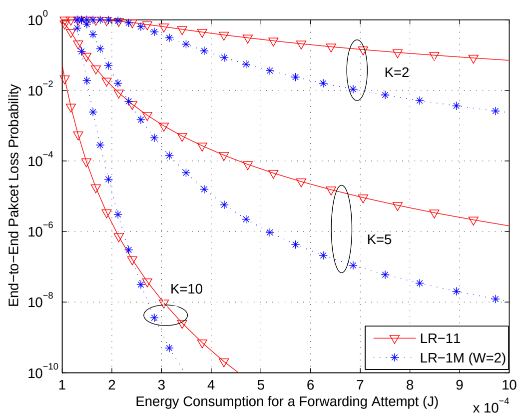

Figure 7. ETE packet loss rate for LR-11 and LR-1M schemes as a function of energy consumption for a forwarding attempt in an equidistant line network with the constraint on the maximum number of transmissions $K = \{2, 5, 10\}$ in truncated ARQ

(3) When $k = i + 1$,

$$
\begin{aligned}
P^{1M}_{t,i+1} &= P_{i-1,i+1}P^{1M}_{t,i-1} + (1 - P_{i,i+2})P^{1M}_{t,i} \\
&= 1 - P^{1M}_{t,i} + (1 - P_{i,i+2})P^{1M}_{t,i} \\
&= 1 - P_{i,i+2}P^{1M}_{t,i}. \qquad (19)
\end{aligned}
$$

Thus, eqn. (8) is proven.

7. REFERENCES

[1] V. Wong, C. Leung, "Effect of Rayleigh Fading in a Multihop Mobile Packet Radio Network with Capture",*IEEE Trans. on Vehicluar Tech.*, pp. 630-637, Vol. 44, No. 3, Aug 1995.

[2] M. Zorzi, R. Rao, "Geographic Random Forwarding(GeRaF) for Ad Hoc and Sensor Networks: Multihop Performance", *IEEE Trans. on Mobile Computing*, pp. 337-348, Vol. 2, No. 4, Oct-Dec 2003.

[3] M. Valenti, N. Correal, "Exploiting Macrodiversity in Dense Multihop Networks and Relay Channels", *IEEE WCNC 2003*, pp. 1877-1882, New Orleans, LA, Mar 2003.

[4] P. Larsson, "Selection Diversity Forwarding in a Multihop Packet Radio Network with Fading Channel and Capture", *Mobile Computing and Communications Reviews*, pp. 47-54, Vol. 5, No. 4, 2001.

[5] B. Zhao, M. Valenti, "Practical Relay Networks: A Generalization of Hybrid-ARQ", *IEEE Journal on Selected Areas in Communications*, pp. 7-18, Vol. 23, No. 1, Jan 2005.

[6] E. M. Royer and C.-K. Toh, "A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks", *IEEE Personal Communications*, pp. 46-55, Apr 1999.

[7] Y. Hua, Y. Chang and Y. Mei, "A Networking Perspective of Mobile Parallel Relays", *IEEE Workshop on DSP*, pp. 249-253, Taos Ski Valley, NM, Aug. 2004.

[8] Z. Ye and Y. Hua, "Networking by Parallel Relays: Diversity, Lifetime and Routing Overhead", *Asilomar Conference on Signals, Systems and Computers*, pp. 1302-1306, Pacific Grove, CA, Nov. 2004.

[9] N. Shacham, E. J.Craighill and A. A.Poggio, "Speech Transport in Packet-Radio Networks with Mobile Nodes", *IEEE Jounral on Selected Areas in Communications*, vol. Sac-1, no. 6, pp. 1084-1097, Dec 1983.

[10] Z. Ye and Y. Hua, "A Route Guided One-to-Many Forwarding Policy over Wireless Relays", Technique Report, Electrical Engineering Department, University of California, Riverside, May 2005.

[11] R. Min and A. Chandrakasan, "Top Five Myths about Energy Consumption of Wireless Communication", *Mobile Computing and Communications Rivew*, Vol. 1, No. 2, pp. 1-2.

[12] P. Chen, B. O'Dea and E. Callaway, "Energy Efficient System Design with Optimum Transmission Range for Wireless Ad Hoc Networks", *IEEE ICC'02*, vol.2, pp. 945-952, Apr 2002.