Hop count optimal position based packet routing algorithms for ad hoc wireless networks with a realistic physical layer

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Abstract*— Existing routing and broadcasting protocols for ad hoc networks assume an ideal physical layer model. We apply the log normal shadow fading model to represent a realistic physical layer and use the probability $p(x)$ for receiving a packet successfully as a function of distance x between two nodes. We define the transmission radius R as the distance at which $p(R) = 0.5$. We propose a MAC layer protocol where receiver node acknowledges packet to sender node u times, where $u * p(x) \approx 1$. We derived an approximation for $p(x)$ to reduce computation time. It can be used as the weight in the optimal shortest hop count routing scheme. We then study the optimal packet forwarding distance to minimize the hop count, and show that it is approximately $0.73R$ (for power attenuation degree 2). A hop count optimal, greedy, localized routing algorithm (referred as *Ideal Hop Count Routing (IHCR)*) for ad hoc wireless networks is then presented. Node C currently holding message will forward it to a neighbor A that minimizes the sum of expected hop count measure from C to A and the ideal hop count between A and destination D. We also present another algorithm called *Expected Progress Routing* with acknowledgements (referred as *aEPR*) for ad hoc wireless networks. Node C currently holding message will forward to a neighbor A (closer to destination than itself) that maximizes $p^2(|CA|)(|CD| - |AD|)$. Two variants of EPR algorithm, namely $aEPR-1$ and $aEPR-u$ are also presented. Next, we propose Projection Progress scheme, where neighbor A that maximizes $p^2(|CA|)(|CD| \cdot |CA|)$, where $CD \cdot CA$ is the dot product of two vectors, is selected, and its two variants, $1-Projection$ and $u-Projection$. We then propose $tR-greedy$ routing scheme, where packet is forwarded to neighbor closest to destination, among neighbors that are within distance tR. All described schemes are implemented, and their performances are evaluated and compared.

I. Introduction

Due to its potential applications in various situations such as battlefield, emergency relief, environment monitoring, etc., wireless ad hoc networks [1], [2], [3], [4] have recently emerged as a premier research topic. Such networks consist of hosts that communicate without a fixed infrastructure. Communications take place over a wireless channel, where each host has the ability to communicate with others in the neighborhood, determined by the transmission range, R. Since there is no infrastructure, every host has to determine its environment when the network is formed.

We assume that each node has a low-power Global Position System (GPS) receiver, which provides the position information of the node itself. If GPS is not available, the distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative co-ordinates of neighboring nodes can be obtained by exchanging such information between neighbors [5].

In the routing task, a message is to be sent from a source node to the destination node. The nodes in the network may be static or mobile. The task of finding and maintaining routes in ad hoc networks is nontrivial since host mobility can result in unpredictable topology changes. We assume in this article that the source node is aware of geographic position of destination. Location updates schemes for efficient routing are reviewed in [6]. Many routing algorithms proposed are non-local and require the complete knowledge and maintenance of the network topology. Recently, many *localized* routing algorithms have been proposed (a brief survey of them is given in [7]), where nodes do not require the complete network topological information to perform the routing task. More precisely, nodes only require the position of itself and its 1-hop neighbors (in some cases also position of its 2-hop neighbors), and position of destination. Consequently, neighboring nodes are aware of distances between them.

We assume that all nodes transmit with equal transmission power. Therefore, all nodes have a fixed and equal transmission radius R, which, however, can be defined in different ways. Existing network layer protocols (with few exceptions, discussed in Section II) for ad hoc networks assume an ideal physical layer model, where two nodes communicate if and only if the distance between them is at most R. In this model, known as the unit graph model, two nodes within transmission radius can exchange correctly bits, packets and messages (we assume that messages are composed of few fixed length packets, and packets are composed of fixed length bit-strings). In the unit graph model there exists therefore the unique transmission radius at all layers of communication. We apply, however, log normal shadow fading model to represent a realistic physical layer. By applying a realistic physical layer, the notion of transmission radius needs to

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be carefully defined and properly used in algorithms. The packet reception probability $p(x)$ depends on the probability of receiving a bit successfully $b(x)$ and the length of the the packet. There are three different ways of determining R so that such function can be applied in protocols. The radius R can be selected so that the probability of receiving a single bit, that is, BER (bit error rate) is 0.5. The second option is to divide message into fixed size packets, and transmit each packet individually. In this case, R can be determined so that packet error rate at distance R is 0.5. The error rate for acknowledgements is then also 0.5 at distance R, since acknowledgements are assumed to be single packets with equal packet length, therefore the same probability for their reception is used. There are variety of ways to define medium access layer for acknowledging the packets. This interpretation for R appears to be the most convenient for deriving protocols and various acknowledgement schemes and we follow this approach in this article. The third option is to decide R for each message separately, so that the probability of receiving message is 0.5 at distance R. In this case R depends on message length, and acknowledgements do not have the same probability of being received.

In this paper, we consider routing with acknowledgements. In the HHR (Hop-by-hop retransmissions) model, a packet is retransmitted between two nodes until it is received and acknowledged correctly. We consider the *separate HHR* variant, where acknowledgements to the previous node and forwarding message to the next node are always done by separate messages. The variant where retransmissions to the next node can serve as acknowledgement to the previous node is left for future research.

Log normal shadowing model provides the computation of the probability $p(x)$ for receiving a packet successfully as a function of distance x between two nodes. This exact computation of $p(x)$, however, is time consuming for nodes that are energy constrained, and does not provide expression that can be conveniently analyzed. We therefore approximate $p(x)$ by a function that reassembles sigmoid function in neural networks, and show that our approximation is reasonably accurate. We then use our approximation as part of proposed routing schemes and in performance evaluations.

We propose to use the expected number of packets between sender and receiver nodes as the new hop count measure between two nodes. We then propose a simple MAC layer protocol where sender node S repeatedly transmits the packet until the acknowledgement from receiver node A is correctly received. The receiver node A acknowledges each correctly received packet u times. We have shown that the best value for u is not a constant, and it appears to be close to the one obtained from solving equation $u * p(x) = 1$. This means that, when the probability of receiving packet becomes low, more acknowledgements needs to be sent to reduce overall expected hop count. The expected hop count is shown to be (under described MAC layer, which is optimal for short messages consisting of one packet) $\left[\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}\right]$. This is then generalized to multi-hop communication. For instance, this expected hop count measure can be used as the weight in the optimal shortest hop count routing scheme, where nodes have global information about the network. We then study the optimal packet forwarding distance to minimize the hop count, and show that it is approximately $0.73R$ (when power attenuation degree is 2), for the considered approximation of $p(x)$.

We redefine the notion of greedy routing, allowing for flexibility in the definition of neighborhood. The localized $tR-greedy$ routing scheme considers all neighbors of node S, currently holding the message, which are closer to destination D than S, and which are at distance at most tR from S.

The rest of the paper is organized as follows. In Section II, we present related work and offer some critical comments. In Section III, we discuss the log-normal shadow propagation model. In Section IV, we present the MAC layer protocol that is used between two wireless nodes along with the derivations. Section V gives the background for our localized, greedy, routing algorithms and derive optimal packet forwarding distance for ideal hop count values. The localized, greedy routing algorithm, called $IHCR$, is presented in Section VI-A. Section VI-B presents another greedy localized protocol, the Expected Progress Routing with acknowledgements ($aEPR$) and two variants. In Section VI-C, we present the Projection Progress algorithm along with two variants. Section VI-D describes modified greedy routing schemes. In Section VII, we provide experimental results and compare the hop count performance of $IHCR$, $aEPR$ and Projection Progress with that of ideal, shortest path and standard greedy schemes. In Section VIII, we provide concluding remarks and outline some open problems in this area.

II. Related Work

There exist a vast amount of literature devoted to position based routing in ad hoc networks. Finn [8] proposed localized greedy scheme, where node, currently holding the message, will forward it to the neighbor that is closest to destination. Only nodes closer to destination than the current node are considered. Another milestone achievement is localized greedy-face-greedy (GFG) algorithm, proposed in [9], which guarantees delivery under ideal MAC layer and correct position information. It applies greedy algorithm whenever possible, and restores to face routing in recovery mode. Face routing uses a planar graph to route from face to face between source and destination nodes. A survey of position based routing schemes is given in [7].

Our work has been inspired by recent observations made in [10], [11], [12], [13]. Qin and Kunz [10] concentrate on the impact of a realistic physical layer (shadowing propagation model) on simulating the performance of well known $AODV$ and DSR on-demand wireless routing protocols. $AODV$ and DSR are non-position based routing schemes, where source issues route discovery via blind flooding (each node receiving route request message will retransmit it once), and destination replies to source using memorized path. Qin and Kunz [10] proposed new signal power thresholds for route discovery to enable the selection of links with strong enough signal strength and reduce some protocol control messages. They report significant increase in the packet delivery ratio and decrease in packet latency, and suggest that link status is a better metric than hop count for selecting routes in shadowing models.

MIT group [11] proposed to use the *expected transmission count metric* (ETX) for finding high throughput paths on multi-hop wireless networks. The ETX metric takes into account the effects of link loss ratios, asymmetry in the loss ratios between the two directions of each link and interference among links of a path. Then they apply ETX metric to $DSDV$ and DSR routing protocols and show that ETX metric improves performance. The protocols are tested on a 29 node 802.11 test-bed. Their observations are based on real implementation, without giving any theoretical results or analysis in support of observations.

Banerjee and Misra [12], [13] considered the cost of re-transmitting messages due to link errors, and derive some optimal formulas and protocols for minimum energy routing. They considered separately end-to-end retransmissions EER (no acknowledgement or error recovery between any two links on a path) and hop-by-hop retransmissions HHR (where message is retransmitted between two nodes until it is received and acknowledged correctly). They first observed that the bit error rate associated with a particular link is a function of the ratio of received signal power to the ambient noise. In the variable-power transmission, they conclude that it is optimal if a transmitter adjusts transmitting power to ensure that the signal strength received by the receiver is independent of the distance d between two nodes. It is not clear what is the optimality measure selected to make this conclusion. It is used, however, as basis to make other conclusions. One immediate consequence of this approach is that, since reception power is fixed, the link error rate between any two nodes is fixed; therefore, probability p_{link} used in expressions is a fixed number. It also follows that transmission power, to achieve that, is proportional to d^{β}, where d is the distance between two nodes S and D. The authors then derive optimal minimum energy paths in EER case. The optimal number of hops N to minimize energy for transmission, assuming that retransmissions from S and D are done until message is received, is computed. The cost of acknowledging back from destination to source is not considered. The authors also considered HHR case, using similar arguments. The problems of finding minimal energy routes appears more difficult than assumed in this article, and we will address it in our future work. In this article, we consider a simpler case of expected hop count optimal routes in HHR case and create basis for later study of power and cost efficient routes.

III. The Log-Normal Shadowing Model

We use the shadow fading model [10] to represent a realistic physical layer. This model can also be used for area coverage calculations, to calculate the probability that the received power is above a threshold value.

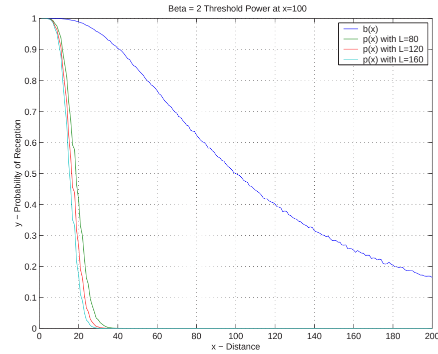

Fig. 1. $b(x)$, and $p(x)$ with $L = 80, 120, 160$ for $\beta = 2$

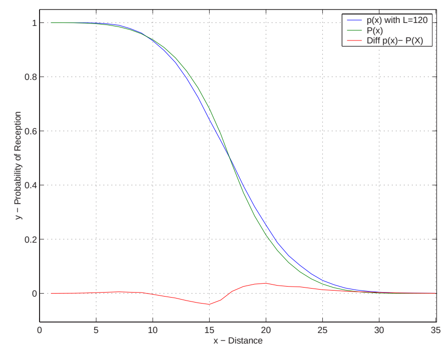

Fig. 2. $p(x)$, $P(x)$, and $p(x)-P(x)$ graphs for $\beta = 2$, $L = 120$, $B = 100$, $R = 16.70$.

We use this as the probability $b(x)$ of receiving a bit successfully. The probability of receiving packet, $p(x)$ is then $p(x) = b(x)^L$, where L is the length of the packet. Note that here we do not assume existence of any error correcting scheme, to recover some incorrectly received bits. Figure 1 plot the probabilities of bit and packet reception, with $\beta = 2$ and $L = 80, 120, 160$, using the shadowing propagation model. The bit transmission radius B is defined as the distance for which $b(B) = 0.5$ and the packet transmission radius R is defined as the distance for which $p(R) = 0.5$ is satisfied.

The exact computation of $p(x)$, for use in routing decisions, is a time consuming process, and is based on several measurements (e.g. signal strengths, time delays, GPS) which are already causing some errors. It is therefore advisable to consider a reasonably accurate approximation that will be fast for use. Having in mind an error within 4%, we designed the following approximation for $p(x)$. We approximated it by $P(x) = (1 - \frac{(\frac{x}{R})^{2\beta}}{2})$ for $x < R$, and $\frac{(\frac{(2R-x)}{R})^{2\beta}}{2}$ for all other x, where β is the power attenuation factor, with fixed value between 2 and 6. We received satisfactory precision with this approximation for $\beta = 2$ and $\beta = 4$ values. One can observe that the power attenuation factor in the approximation is 2β rather than β. This is due to approximating packet probability rate rather than bit probability rate, and the greater impact of packet length on packet reception at larger distances. Our best approximation for bit probability rate is, in fact, the same expression except that power attenuation factor is β instead of 2β. We anticipate that, in general, power attenuation factor $q\beta$ can be used, where q depends on L. Note that in the sequel we still use the notation $p(x)$ although the results were in fact derived using its approximation $P(x)$.

Figure 2 shows the difference between $p(x)$ and the selected approximation $P(x)$ for $\beta = 2, L = 120$. The observed relative error of the approximation is below 4% for $x \leq 2R$. We repeated the process for $\beta = 4$ and also received similar error bounds.

IV. MAC Layer Protocol Between Two Nodes

In this section, we consider HHR (hop-by-hop retransmission) routing protocol, where the sender of a packet requires the acknowledgement from receiver. To simplify our protocols and analysis, we assume that receiving node needs to send separate acknowledgement and forwarding packets to the previous and the next nodes on the route. We describe a simple MAC layer communication protocol between two nodes and present related analysis. After receiving any packet from sender, the receiver sends u acknowledgements. If the sender does not receive any acknowledgement, it retransmits the packet. We then derive the expected number of messages in this protocol, which is our proposed measure of hop count between two nodes. The count includes transmissions by sender and acknowledgments by receiver. Both the acknowledgement and data packets are of same length. This hop count is then used as weight in the shortest hop count path algorithm, for performance comparisons.

Let S and A be the sender and receiver nodes, respectively, and let $|SA| = x$ be the distance between them. The generic protocol for sending a packet from S to A is described as follows:

```
S-recd-ack=false
Repeat
   S sends packet to A
   If that packet is received at A
     {A sends u acks to S;
      If one ack received at S
        then S-recd-ack=true}
Until S-recd-ack
```

Probability that A receives the packet from S is $p(x)$. Probability that S receives one particular packet from A is $p(x)$ and the probability that it does not receive the packet is $1 - p(x)$. Therefore, the probability that S does not receive any of the u acknowledgements is $(1 - p(x))^u$. Thus, the probability that S receives at least one of u acknowledgements from A is $1-(1-p(x))^u$. Therefore, $p(x)(1-(1-p(x))^u)$ is the probability that S receives acknowledgement after sending a packet and therefore stops transmitting further packets. Thus, the expected number of packets at S is

$$\frac{1}{[p(x)(1-(1-p(x))^u)]}.$$

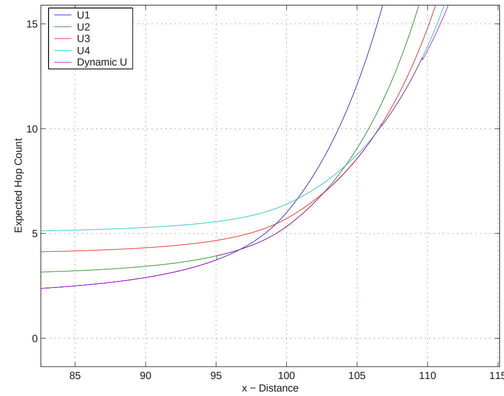

Fig. 3. Dynamic calculation of u value with $\beta = 4$, $R = 100$.

Each of these packets is received at A with probability $p(x)$. If received correctly, it generates u acknowledgements. The total expected number of acknowledgements sent by A is then

$$\frac{up(x)}{[p(x)(1-(1-p(x))^u)]} = \frac{u}{[(1-(1-p(x))^u)]}.$$

The total expected hop count between two nodes at distance x is then

$$\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}.$$

For low values of x, the best choice of u is 1. However, for larger values of x, probability $p(x)$ becomes low, and therefore, once received, packet may need to be retransmitted few times for successful acknowledgement and a different value of u could be more efficient. Each value of u is an optimal choice for some range of x values. We can devise a mechanism to dynamically calculate the value of u for a given probability $p(x)$, such that $u * p(x) = 1$. So determined value of u is the one for which the expected number of received acknowledgements is 1, hence the choice. Thus the best choice of u for a given $p(x)$ is $round(1/p(x))$. This choice can be further optimized by using delayed rounding-off ($(round((1/p(x)) - .1)$) to reduce the hop count variations between u transitions. In our simulations, depending on the value of $p(x)$, we dynamically calculate the u value. Figure 3 shows the expected hop count for $u = 1, 2, 3, 4$ and confirms that dynamically calculated u values using the above method are optimal choices for different probability values.

Thus the choice of u does not need to be fixed in MAC protocol. It can be dynamically calculated using the $p(x)$ value for optimal hop count performance. This expected hop count can be used as a weight in the Dijkstra's shortest path algorithm to derive hop count optimal paths between any two nodes. We have used it as a hop count optimal and best possible scheme and compared with our localized schemes, $IHCR$, $aEPR$ based algorithms, $ProjectionProgress$ based algorithms and $tR - greedy$, described in coming sections.

	u = 1	u = 2	u = 3
β = 2	0.7272R	0.8335R	0.8920R
β = 4	0.7902R	0.8680R	0.9065R

Fig. 4. Optimal Forwarding distances with $u = 1, 2, 3$ for $\beta = 2, 4$.

	u = 1	u = 2	u = 3
β = 2	3.4572 d/R	4.2271 d/R	5.1674 d/R
β = 4	2.8519 d/R	3.7755 d/R	4.7952 d/R

Fig. 5. Ideal Expected Hop Count with $u = 1, 2, 3$ for $\beta = 2, 4$.

V. Optimal Packet Forwarding Distance is Less Than Transmission Radius

In this section, we show that the optimal packet forwarding distance to minimize the hop count is less than the transmission radius R. To derive this result, we place $(n-1)$ equally spaced additional nodes, if needed and desired, between source S and destination D, along the straight line joining S and D. Let $x = d/n$ be the distance between two consecutive nodes. We now derive the optimal values for n and x, by finding the expected hop count of such placement, and finding its minimum analytically. We then show that such an ideal placement is achieved for $x < R$.

By applying the earlier analysis in Section IV, the total expected hop count from source to destination is

$$\frac{d}{x}\left[\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}\right].$$

In order to discuss optimizing a function independently on particular distance d, and particular transmission radius R, we consider then optimizing instead the function

$$h(x,u,\beta,R) = \frac{R}{x}\left[\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}\right]$$

For $\beta = 2$ and $u = 1$, using our approximation for $p(x)$, we derived the minimum 3.4572 at $x = 0.7272R$, and the ideal expected hop count is $3.4572\frac{d}{R}$. The optimal forwarding distances and ideal expected hop count values for different $u = 1, 2, 3$ and $\beta = 2, 4$ are given in Figures 4 & 5. The expected hop count is minimal for $u = 1$, which is the choice made in the $IHCR$ routing scheme described below. Figure 6 shows $IHC(u, \beta, R)$ as a function of x, for $\beta = 2$. The expected hop count is obtained when these normalized values are multiplied by $\frac{d}{R}$. We can observe that the expected hop count values are low in the range approximately $0.60R$ to $0.90R$ for $u = 1$, about 50% higher at $x = R$ and very high for $x > R$. For small x, the expected hop count is very high (and is not even shown in the figure, where x starts from $0.1R$).

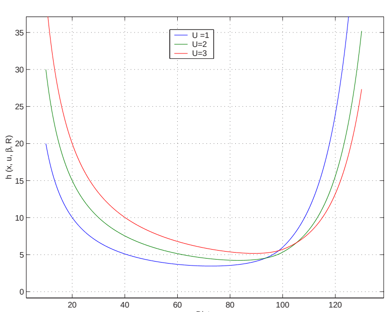

Fig. 6. Hop Count as a function of distance x, for different u ($\beta = 2$).

VI. Localized, Physical Layer based Routing Algorithms

A. A Hop Count Optimal, Greedy Localized Routing Algorithm

In this section, we design a greedy routing protocol with hop by hop acknowledgements. We name it *Ideal Hop Count Routing* $(IHCR)$ since it is based on the ideal packet forwarding, presented in the previous section.

Let C be the node currently holding the packet destined for D. Node C will forward it to a neighbor A (closer to destination than itself) that minimizes the sum of the expected hop count measure from C to A and the ideal hop count between A and destination D (as derived in the previous section). More precisely, the neighbor A that minimizes $(\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}) + \frac{a}{R}IHC(1,\beta,R)$ is selected, where $x = |CA|$ and $a = |AD|$. The value of u is dynamically calculated based on distance $x = |AC|$, as described in Section IV. Only neighbors closer to the destination than C are considered. In the last term, however, the value for u is fixed at $u = 1$, since that choice gives the best expected performance in ideal conditions. The process continues until the destination is reached, or a node is reached that has no neighbor closer to the destination.

B. Expected Progress Routing (aEPR) Algorithms

Let the current node be C, destination be D, and A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$. The progress made by forwarding from C to A is $(c-a)$. Regular greedy scheme maximizes $(c-a)$, by sending to a neighbor closest to the destination (minimizes a).

The progress that can be made by sending a packet to A is probabilistic. In $aEPR$ algorithm, a node C currently holding the packet will forward it to a neighbor A (closer to destination than itself) that maximizes the expected progress, which is the product of the probability of successful delivery of the packet from C to A and the progress made $(|CD| - |AD|)$ by forwarding to A. In $aEPR$, the neighbor A that maximizes $p^2(x)(c-a)$ is selected.

The progress that can be made by sending a packet to A can also be considered with respect to the cost measure for making such progress. The cost measure considered is the expected hop count. The expected hop count depends on distance and

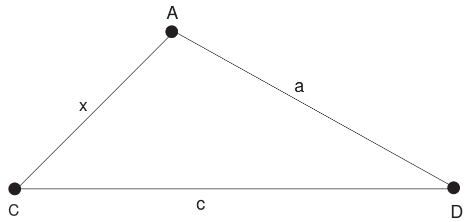

Fig. 7. Selecting the *best* neighbor A in localized routing schemes.

selected number u of acknowledgements. The progress made could be measured in different ways. In this section, the progress made by forwarding to node A is $(|CD| - |AD|)$. In the next section, it will be defined differently.

Consider first the fixed value $u = 1$ in $aEPR$ algorithm. In this algorithm, called $aEPR - 1$, a node C currently holding the packet will forward to a neighbor A (closer to destination than itself) that maximizes the ratio of expected progress and cost for the progress made. Since the considered cost, expected hop count, is $1/p(x)^2 + 1/p(x)$, $aEPR - 1$ will select the neighbor A that maximizes $(c - a)/(1/p(x)^2 + 1/p(x))$.

Now consider the variant of the algorithm where best value of u is selected. The best value of u is approximated as $u = round((1/p(x)) - .1)$. The expected hop count is then $f(u, x) = \frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}$. This variant, called $aEPR - u$, will select neighbor that maximizes $(c - a)/f(u, x)$.

C. Projection Progress Routing Algorithm

Let the current node be C, destination be D, and A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$.

Projection Progress based algorithms differ from $aEPR$ schemes in the progress measure only. Instead of $c - a$, it is measured by dot product $(|CD| \cdot |CA|)$. In the $ProjectionProgress$ scheme, a node C, currently holding a packet, will forward it to a neighbor A (closer to destination than itself) that maximizes $p^2(|CA|)(|CD| \cdot |CA|)$, where $CD \cdot CA$ is the dot product of two vectors.

By substituting this new progress measure in $aEPR - 1$ and $aEPR - u$, we obtain two new routing schemes called $1 - Projection$ and $u - Projection$ progress, respectively.

D. Greedy forwarding

The well known greedy routing scheme, proposed by [8], works as follows. Node C, currently holding the packet, will forward it to the neighbor (among neighbors closer to destination than itself) that is closest to the destination. This algorithm is unambiguous with the existing definition of transmission radius in ideal unit graph model. However, with a realistic physical layer, it can receive different interpretations. We therefore modify its definition to accommodate the log normal shadowing model as follows. Consider as neighbors all nodes that are located at distance at most tR from C. Among these nodes, select one that is closest to destination (among those that are closer to destination than C).

It was observed that the packet probability rate drops to near 0 at distance $2R$. Therefore the value $t = 2$ may be interpreted as sufficient to include all neighbors with sufficient packet probability rate to establish communication with C via some repeated hello messages. For example, if packet probability rate is 0.2, it is expected that one out of five transmitted hello messages can reach the neighboring nodes, so that node might be used for forwarding messages. However, such choices do not necessarily lead to optimal values for expected hop counts. As will be seen in experimental results, a neighbor at distance close to $2R$ may have extremely high expected hop count. We therefore believe that a better performance will be achieved if $t < 2R$. We tested for different choices of t.

VII. Experimental Results

In this section, we present the results of our simulation study. For the simulation, we use a 300×300 area for the placement of wireless nodes. Each of n nodes ($n = 250$) is selected uniformly at random inside the square area.

Dijkstra's shortest path scheme was used to test network connectivity, and only connected graph were used in measurements. The network density d is defined as the average number of neighbors per each node using the unit graph model. Two nodes are considered neighbors in this graph if and only if the distance between them is at most hR, where $p(R) = 0.5$ and hR is the distance such that $p(hR) = w$, for suitably selected threshold value w. Based on our approximation function, and value $w = 0.05$, the obtained $h = 1.4377$. We select d as independent variable, and then find the appropriate value for R, which depends on network area size. Then this value of R is used in the approximation $P(x)$ for $p(x)$. The proposed experimental design allows for flexibility in the neighbor definition by selecting appropriate density. For example, if two nodes are considered as neighbors only when their distance is at most tR, then the corresponding density d' of a graph is approximately $d' = (t/1.4377)^2 d$, where d is the density that corresponds to $1.4377R$ neighbors. All the density values reported in tables are with respect to $1.4377R$ neighbors. We tested for $d = 6, 8, 10, 20, 24, 32, 40$ and 80. The average values are reported over 500 simulations (graphs). The value of u is dynamically calculated based on the $p(x)$ value. We have used $\beta = 2$. We tested some other parameter settings, but the relative comparison remained the same.

We compared the success rates and expected hop count performance of $IHCR$, $aEPR$, $aEPR - 1$, $aEPR - u$, $ProjectionProgress$, $1 - Projection$, $u - Projection$ progress, $tR - greedy$ for $t = 1$, $t = 1.25$ and $t = 1.4377$ and shortest path algorithms (where link weights are computed as explained in Section IV). The *ideal* routing, where nodes between sender and destination can be placed at will, is also added as a reference. We measured hop counts only for source-destination pairs where all of competing methods successfully found their routes to destination (with the exception of very low densities where the success rate of R and $1.25R$ greedy methods are near zero; in these cases these protocols were ignored while averaging expected hop counts). We define the

Algorithm	Number of Nodes : 250							
	Density (with 1.4377R neighbors)							
	6	8	10	20	24	32	40	80
Ideal	0.555	0.591	0.651	0.831	0.855	0.887	0.910	0.946
Shortest Path	1	1	1	1	1	1	1	1
aEPR	1.335	1.356	1.355	1.123	1.069	1.065	1.049	1.038
aEPR-1	1.309	1.357	1.372	1.124	1.069	1.067	1.048	1.036
aEPR-u	1.362	1.392	1.426	1.145	1.093	1.077	1.057	1.037
IHCR	1.348	1.356	1.356	1.107	1.067	1.060	1.047	1.035
Proj Progress	1.343	1.344	1.347	1.123	1.071	1.075	1.060	1.062
1-Projection	1.320	1.348	1.341	1.119	1.069	1.073	1.059	1.063
u-Projection	1.343	1.373	1.380	1.129	1.084	1.074	1.062	1.064
1.4377R Greedy	3.576	3.701	4.140	5.477	5.827	6.250	6.715	7.316
1.25R Greedy	1.618	1.676	1.790	2.331	2.439	2.565	2.709	3.008
R Greedy	1.034	1.058	1.091	1.160	1.163	1.201	1.224	1.276

Fig. 8. Hop count performance of the algorithms for different densities ($\beta = 2$).

hop count dilation as the ratio of the expected hop count performance of the specific algorithm to that of the shortest path. The hop count dilation ratios are given in Figure 8. Figure 9 gives the success rate of these algorithms.

It can be observed from tables that $IHCR$, $aEPR$ and Projection progress based localized algorithms had very similar performances. Therefore, all the schemes remain candidates for future extensions (e.g. to routing scheme with guaranteed delivery). Most importantly, at higher densities, $aEPR$, $IHCR$ and Projection Progress protocols had only relatively small additional hop counts with respect to the shortest weighted path algorithms, which requires global information. This is a very important achievement for localized routing schemes.

The performance of $tR{-}greedy$ routing algorithm was very dependant on the selected t value. For higher t, both success rates and hop count measures increase. The success rate for $t = 1$ and $t = 1.25$ is low, while hop count for $t = 1.4377$ is high. We tested more values of t in $tR - greedy$ algorithm $(t = 1.4, 1.6, 1.7)$ but received either very high hop count or low success rates, and value $t = 1.25$ appears near best possible. Therefore, we concluded that $tR - greedy$ scheme is inferior to other localized routing schemes proposed in this article for all values of t.

VIII. Conclusion

To the best of our knowledge, this is the first study of position based routing in ad hoc network with a realistic physical layer. We investigated routing with hop by hop acknowledgements, and presented several greedy routing algorithms for ad hoc wireless networks, based on realistic physical layer assumptions. These include ideal hop count routing, expected progress routing and projection progress routing. We show that realistic physical layer does have impact on the choice of best localized scheme.

The localized nature of the protocols avoids the energy expenditure and communication overhead needed to build and maintain the global topological information. Our simulation results show that, for higher densities, the performance of our localized algorithms is close to the performance of the shortest (weighted) path algorithms, which require global knowledge.

We plan to address, in our future research, several problems, including forwarding messages composed of several packets, power and cost aware localized routing, adjusting GFG routing with guaranteed delivery [9], and route discovery in reactive routing (when received signal strength is measurable, or position information is available) to take into account realistic physical layer. Our group is also currently working on broadcasting problem and location updates for efficient routing, with the realistic physical layer.

A number of other extensions to presented work remain as open problems for future research. For instance, we considered only separate HHR model, while one could study also model where forwarding messages may be used also as acknowledgement messages. We considered only a simple packet reception model, bit by bit. If some error correcting codes are applied, the packet probability rate will also change. New approximation of $p(x)$ is then needed, which may impact the performance of algorithms. Appropriate MAC layer protocols may be required to accommodate considered coding schemes. Finally, we considered log normal shadowing model. It is possible to consider other models for physical layer, such as Raleigh fading.

Algorithm	Number of Nodes : 250							
	Density (with 1.4377R neighbors)							
	6	8	10	20	24	32	40	80
Shortest Path	100%	100%	100%	100%	100%	100%	100%	100%
aEPR	36%	50.4%	74.4%	100%	100%	100%	100%	100%
aEPR-1	36.4%	52%	75.2%	100%	100%	100%	100%	100%
aEPR-u	37.6%	51.6%	75.6%	100%	100%	100%	100%	100%
IHCR	33.2%	47.6%	70.8%	100%	100%	100%	100%	100%
Proj Progress	34.4%	49.2%	73.2%	100%	100%	100%	100%	100%
1-Projection	35.6%	51.2%	75.2%	100%	100%	100%	100%	100%
u-Projection	36.8%	51.2%	75.6%	100%	100%	100%	100%	100%
1.4377R Greedy	45.2%	68.8%	81.2%	100%	100%	100%	100%	100%
1.25R Greedy	12%	26.8%	50.4%	98.4%	98.8%	100%	100%	100%
R Greedy	0.4%	1.2%	6%	81.6%	89.6%	99%	100%	100%

Fig. 9. Success rate of the algorithms for different densities ($\beta = 2$).

We have further improved *aEPR* and *Projection Progress* algorithms with their iterative versions. In *Iterative aEPR*, we first find a neighbor node A that maximizes $p^2(|CA|)(|CD| - |AD|)$, as in *aEPR*, where C and D are the source and destination nodes respectively. Then we iteratively find a neighbor node B of C and A (where B is closer to D than C), with maximum $p^2(|CB|)p^2(|BA|)$ measure, while satisfying $p^2(|CB|)p^2(|BA|) > p^2(|CA|)$. The *Iterative Projection Progress* scheme is very similar to *Iterative aEPR*, except that the first neighbor node A maximizes the $p^2(|CA|)(|CD|.|CA|)$ measure.

In this article we studied the case with fixed length packets. We are now designing routing algorithms for the case of variable packet length, whose length is adjusted to achieve optimality for each hop on the route. A route discovery based routing scheme for the case of hop by hop acknowledgements with variable packet length has been studied recently in [14]. In [15], we describe localized routing algorithms with acknowledgments, with variable packet lengths on each hop. Instead of expected hop count in terms of packets, these schemes measure expected number of transmitted bits. In [16], we describe localized routing algorithms with variable packet lengths on each hop but without any hop-by-hop acknowledgments. These algorithms try to maximize the probability of delivery of the packets to the destination.

We anticipate that this direction of research will soon receive more attention in the ad hoc networks research community.

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