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Greedy localized routing for maximizing probability of delivery in wireless ad hoc networks with a realistic physical layer

Johnson Kuruvila*, Amiya Nayak, Ivan Stojmenovic

School of Information Technology & Engineering, University of Ottawa, Ottawa, Ont., K1N 6N5, Canada

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Abstract

Almost all existing routing and broadcasting protocols for ad hoc networks assume an ideal physical layer model. In this article, we present new greedy, localized algorithms for ad hoc wireless networks for maximizing probability of delivery, without acknowledgements, considering a realistic physical layer. Using the log normal shadowing model to represent a realistic physical layer, we use the probability $p(x)$ for receiving a packet successfully as a function of distance x between two nodes and define the transmission radius R as the distance at which $p(R) = 0.5$. The probability $p(x)$ of receiving a packet of length L is computed as $b(x)^L$ where $b(x)$ the probability of successfully receiving a bit. In *Expected Progress Routing*, without acknowledgements (referred as *nEPR*), a node S currently holding message, destined for node D, will forward to a neighbor A (closer to destination than itself) that maximizes $p(|SA|)(|SD| - |AD|)$. In *Iterative Expected Progress Routing* (referred as *InEPR*), we first find a node A that maximizes $p(|SA|)(|SD| - |AD|)$ as in *nEPR* and then iteratively find an intermediate neighbor node B of S and A (B is closer to D than S) with maximum $p(|SB|)p(|BA|)$ measure, while satisfying $p(|SB|)p(|BA|) > p(|SA|)$. In Projection Progress algorithm, a neighbor that maximizes $p(|SA|)(SD \cdot SA)$ is selected to forward the message. An improved variant, Iterative Projection Progress, similar to *InEPR* is also presented. We also present the *EER* (end-to-end routing) protocol, where the probability of end-to-end successful delivery is maximized and show that it is same as the *NC* (Nearest Closer) method proposed earlier. The algorithms, *nEPR*, *InEPR*, Projection Progress, Iterative Projection Progress and *EER* (NC) schemes are implemented and their performance evaluated and compared with that of shortest path and *tR* greedy schemes. Our newly proposed localized routing protocols are performing better than the greedy routing schemes which forwards the packet to neighbor closest to destination.

Keywords: Ad hoc wireless networks; Sensor networks; Routing; Broadcasting; Physical layer

1. Introduction

Due to its potential applications in various situations such as battlefield, emergency relief, environment monitoring, etc., wireless ad hoc networks [3,7,8,14] have recently emerged as a premier research topic. Ad hoc networks are 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 it is infrastructure-less, 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 [13].

Routing is the task of delivering a message from the source node to the destination node. The network may consist of static or mobile nodes. 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 [16]. Many routing algorithms proposed are non-local and require the complete knowledge and maintenance

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* Corresponding author.

E-mail addresses: kuruvila@site.uottawa.ca (J. Kuruvila), nayak@site.uottawa.ca (A. Nayak), ivan@site.uottawa.ca (I. Stojmenovic).

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of the network topology. Recently, many *localized* routing algorithms have been proposed (a brief survey of them is given in [17]), 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. Practical routing algorithms for ad hoc networks should be localized in order to reduce otherwise huge communication overhead required for global updates due to node mobility and changes in activity status.

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 Related work section) 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 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 packet. We assume that the message is decomposed into packets, each transmitted separately. Consequently, we define transmission radius *R* so that packet error rate at distance *R* is 0.5.

In our previous work [9], we considered the routing task with acknowledgements and presented a number of schemes that minimize the hop count measure from the source to the destination. In this article, we consider the routing task without message acknowledgements and propose several new routing schemes. We propose the *Expected Progress Routing* algorithm without acknowledgements (*nEPR*), where the current node *S* holding a message for destination *D* will forward to a neighbor *A* (closer to *D* than *S*), which maximizes $p(|SA|)(|SD| - |AD|)$, which is the measure of progress made. The *Iterative Expected Progress Routing* (*InEPR*) is an improved variant of *nEPR*, where we first find a neighbor node *A* as in *nEPR* and then iteratively find intermediate nodes *B* (if exists), between *S* and *A* (and neighbor to both *S* and *A*) with maximum $p(|SB|)p(|BA|)$ measure that satisfies $p(|SB|)p(|BA|) > p(|SA|)$. The *Projection Progress* algorithm is very similar to the *nEPR* algorithm except for the measure of progress. A current node *S* holding a message for destination *D* will forward to a neighbor *A* (closer to *D* than *S*), which maximizes $p(|SA|)(SD \cdot SA)$, where $(SD \cdot SA)$ is the new progress measure and the dot product of two vectors. In the improved variant *Iterative projection progress*, the first forwarding neighbor node is found using the projection progress method and is iteratively improved by finding better intermediate nodes as in the *InEPR* algorithm. We also propose the *EER* (end-to-end routing) algorithm, without acknowledgements, where the probability of successful delivery of a message from the source to destination is maximized. We show that the *EER* scheme is same as the *NC* algorithm presented in [19]. In *NC* (Nearest Closer) scheme, current node *S* forwards the packet to the nearest neighbor among neighbors that are closer to destination than *S*.

The probability of successful delivery of the packet (which is the product of all the probabilities of successful delivery between two intermediate hops along the found route) from source to destination is used as a performance measure for all the proposed algorithms. We also use the success rate of finding a route between the source and the destination nodes as another performance measure. These performance measures, the probability of successful delivery and success rates of all the methods are compared with that of Shortest path, and *tR* greedy schemes [9] with *t* values of 1, 1.5 and 2. The redefined notion of greedy routing as described in [9], allows for flexibility in the definition of neighborhood. The localized *tR-Greedy* routing scheme considers all neighbors of node *S* (node currently holding the message), which are closer to destination *D* than *S*, and which are at distance at most *tR* from *S*. Among those neighbors, it selects one that is closest to destination.

The rest of the paper is organized as follows. In Section 2, we present some related work. In Section 3, we briefly discuss the log normal shadow propagation model. A realistic physical layer is modelled using this model. The *EER* algorithm and the related analysis is presented in Section 4. Sections 5 and 6 present the greedy localized protocols, the Expected Progress Routing (*nEPR*) and Iterative Expected Progress Routing algorithms respectively. In Section 7, the Projection Progress and the Iterative Projection progress schemes are presented. In Section 8, we provide experimental results and compare the performances of *nEPR*, *InEPR*, Projection Progress, Iterative projection progress and *EER* (NC) schemes with that of shortest path and *tR* greedy schemes (with $t = 1, 1.5, 2$). The proposed localized routing schemes outperform *tR* greedy routing schemes [6] where packet is forwarded to neighbor (within the considered neighborhood) that is closest to destination. In Section 9, we provide concluding remarks and outline some open problems in this area.

2. Related work

There exist a vast amount of literature devoted to position based routing in ad hoc networks. Finn [6] 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 [4], 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 [17].

Our work has been inspired by recent observations made in [1,2,5,9,15]. Qin and Kunz [15] 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 [15] 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.

Banerjee and Misra [2,1] considered the cost of retransmitting 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 optimality claim, however, is not acceptable due to erroneous assumption made.

In [9], authors use the log normal shadow fading model to represent a realistic physical layer, and for computing the probability of receiving a packet as a function $p(x)$ of distance x between two nodes. The transmission radius R is determined by $p(R) = 0.5$. For the ease of computation, a reasonably accurate approximation for $p(x)$ is also presented. Many new routing schemes that optimize hop count measure from source to destination are presented in this article. The authors also redefine the notion of greedy routing by 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. In this article, use the same approximation for $p(x)$ as in [9] and use *tR-Greedy* schemes for performance comparisons.

3. The shadow propagation model

Most of the published results in ad hoc wireless routing and broadcasting are based on free-space or two-ray ground propagation models, which are simplistic and idealistic physical layer models. However in real scenarios, the received signal strength is not only dependent on the distance between the transmitter and the receiver but also on the environment. Moreover, subsequent transmissions with the same transmission power, between same nodes in the same environment are not received with the same signal power. This means that, depending on threshold for correct reception, that message may or may not be received based on some random events. Following [15,9], we model a realistic physical layer using the shadow propagation model, where the noise element is modelled by a gaussian distribution. This model can also be used for area coverage calculations, to calculate the probability that the received power is above a threshold value.

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. Fig. 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% and value $L = 120$, 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 (that is, value $L = 1$) 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 $P(x)$.

Fig. 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 $x \leqslant 2R$. We repeated the process for $\beta = 4$ and also received similar error bounds, as shown in Fig. 3.

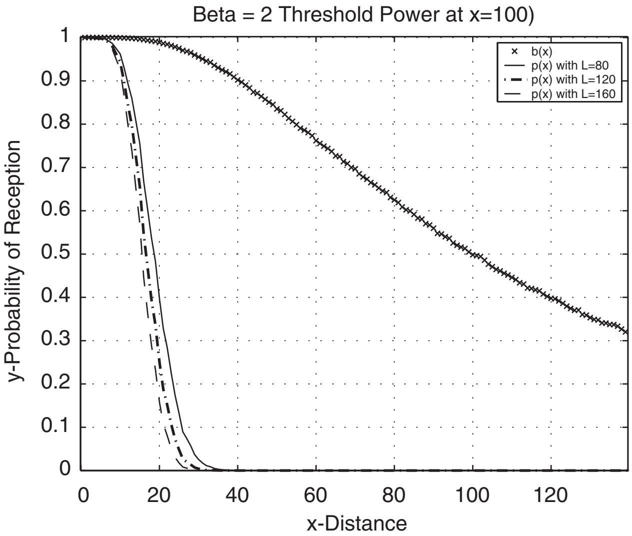

Fig. 1. $b(x)$, and $p(x)$ with $L = 80, 120, 160$ for $\beta = 2$.

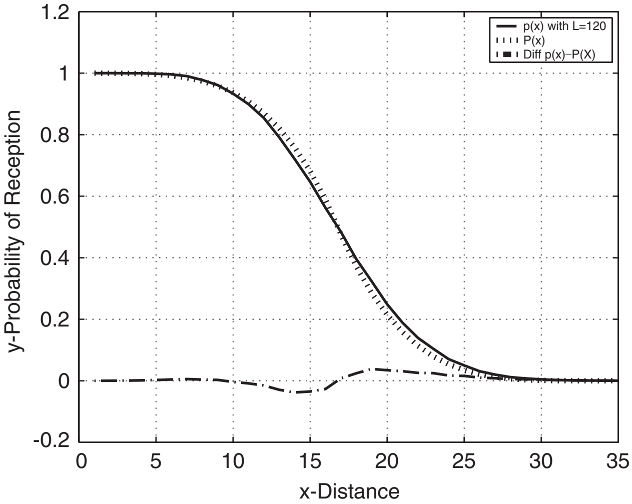

Fig. 2. $p(x)$, $P(x)$, and $p(x) - P(x)$ for $\beta = 2, L = 120$.

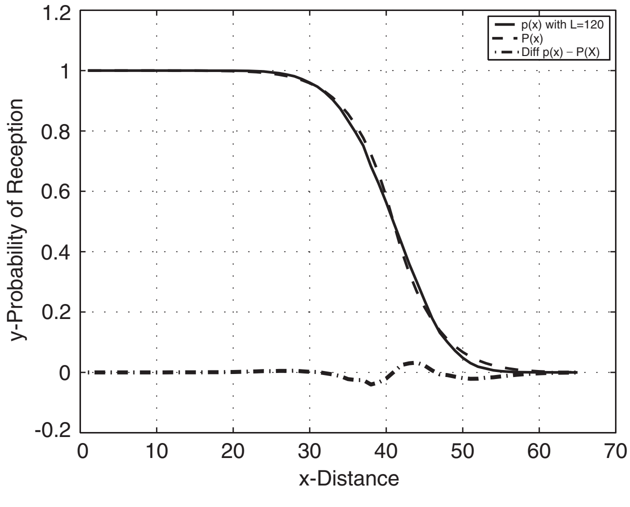

Fig. 3. $p(x)$, $P(x)$, and $p(x) - P(x)$ graphs for $\beta = 4, L = 120$.

4. EER (end-to-end routing) localized routing

In the EER model, there are no hop-by-hop acknowledgements. When (and if) a message arrives at the destination, there may or may not be acknowledgments sent from the destination to the source node, as a routing task. We consider, for detailed study and experimentation, the no-acknowledgment variant of the EER model.

Consider the routing task of sending a message from source C to destination D. Consider intermediate nodes at distances $x_1, x_2, \ldots, x_n$. The probability that D receives the full message from C is $p(x_1)p(x_2), \ldots, p(x_n)$, which needs to be maximized. This is equivalent to maximizing $\log(p(x_1)p(x_2), \ldots, p(x_n)) = \log(p(x_1)) + \log(p(x_2)) + \cdots + \log(p(x_n))$. The shortest weighted path algorithm can be applied to find the route with maximal probability of delivering packet by assigning $-\log(p(x_1)), -\log(p(x_2)), \ldots, -\log(p(x_n))$ as the respective weights for the links.

In order to derive an ideal EER algorithm, consider placing $n-1$ equally spaced nodes between the source and destination nodes, S and D. Let $x = \frac{d}{n}$ be the distance between the two consecutive nodes, where $|SD| = d$. The probability of receiving a message at the destination D is $p(x_1)p(x_2), \ldots, p(x_n) = (p(x))^n$. By taking the logarithm, this can be written as $n \log(p(x)) = \frac{d}{x} \log(p(x))$, which needs to be optimized for the optimal placement distance x and for calculating ideal probability.

By applying l'Hôpital's rule, and the approximation for $p(x)$, we can show that, for the function $\frac{d}{x} \log(p(x))$, the optimal value of x is 0 and the ideal probability is 1.

Following this observation, a localized EER algorithm can be described as follows. The node C currently holding a message will forward it to a neighbor A (closer to destination that itself) that maximizes the sum of logarithmic probability to deliver to A and ideal logarithmic probability of delivering from A to D. However, the later ideal probability is 1 (that is, the logarithmic probability is 0). Therefore, the algorithm simply forwards the packet to neighbor A that maximizes $p(x)$, where $x = |CA|$, which is the closest neighbor to C among nodes which are closer to D than C. The process continues until the destination is reached or a node is reached that has no neighbor closer to the destination.

The described localized algorithm will also be referred to as the *NC* (nearest closer) routing scheme. This localized routing scheme was already proposed in [19].

5. Expected progress routing (nEPR) algorithm

Let the current node be C, destination be D, and A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$ (see Fig. 4). The progress made by forwarding from C to A is $c - a$. 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 message to A is probabilistic. In non-acknowledged progress routing (*nEPR*) algorithm, a node C currently holding the message will forward to a neighbor A (closer to destination than itself) that maximizes

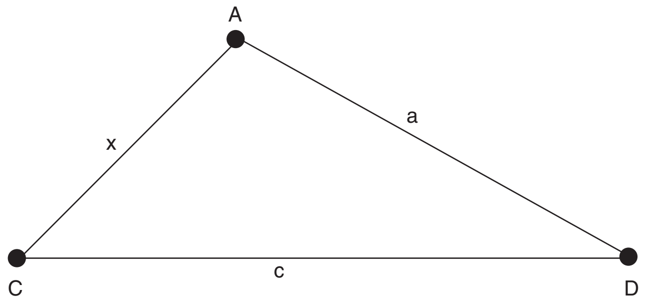

Fig. 4. Selecting the *best* neighbor *A* in localized routing schemes.

the expected progress, which is the product of the probability of successful delivery $p(x)$ of the message from C to A and the progress made $(|CD| - |AD|)$ by forwarding to A. Therefore, the neighbor A that maximizes $p(x)(c-a)$ is chosen to forward the message.

6. Iterative expected progress routing (InEPR) algorithm

The Iterative Expected Progress Algorithm (*InEPR*) is an improved variant of *nEPR*. The algorithm can be described as follows. As in *nEPR*, a node C currently holding a message will first find a neighbor A that maximizes $p(|CA|)(|CD| - |AD|)$. Then, an intermediate node B (closer to destination than C, if exists) is found (that is neighbor to both C and A) which satisfies $p(|CB|)p(|BA|) > p(|CA|)$ and has the maximum $p(|CB|)p(|BA|)$ measure. This process is iteratively repeated until no improvement is possible. Node C will forward the message to the selected neighbor B which than applies again the same scheme for its own forwarding. A pseudo code of the algorithm can be written as

```
Current Node C, Destination D,
Find best nEPR Neighbor A such that
      p(|CA|)(|CD|-|AD|) is maximum
Candidate_node, M = A.
Repeat
 Max = p(|CM|); Selected_Neighbor,
     N = M (Candidate_node)
 For each neighbor B of C
       (which is closer to D than C)
   If B is neighbor of M (Candidate_node)
     If p(|CB|)p(|BM|) > Max
      Max = p(|CB|)p(|BM|);
      Candidate_node, M = B
     End
   End
Until Candidate_node,
     M = Selected_Neighbor, N.
```

7. Projection progress algorithms

Let the current node be C, destination be D, and A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$. Projection progress based algorithms differ from *nEPR* schemes in the progress measure only. Instead of $c - a$, it is measured by dot product $(CD \cdot CA)$. In the *Projection Progress* scheme, a node C, currently holding a packet, will forward it to a neighbor A (closer to destination than itself) that maximizes $p(|CA|)(CD \cdot CA)$, where $(CD \cdot CA)$ is the dot product of two vectors.

The iterative projection progress scheme is very similar to *InEPR*, except that the first candidate node A is found using the projection progress method, (maximizes $p(|CA|)(CD \cdot CA)$), instead of *nEPR* scheme.

8. 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. Two nodes are considered as neighbors if and only if their distance 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 $w = 0.05$, 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 figures 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). We have used $\beta = 2$. We tested some other parameter settings, but the relative comparison remained the same.

The two performance measures we have used to compare the algorithms are the success rate and the probability of successful delivery. Success rate measures the rate of success in finding a route from the source to the destination in the attempted cases. The probability of successful delivery is the product of all probabilities of successful delivery along all hops of the computed route. The success rates in finding a route and probability of successful delivery along the found route to the destination are computed for the *nEPR*, *InEPR*, Projection progress, Iterative Projection Progress and *EER* (NC) algorithms. Their performance is compared with that of *tR* greedy [9] (with t values 1, 1.25 and 1.4377), and globalized shortest (weighted) path algorithm. The weight assignment scheme is as described in Section 4. The probabilities of delivering along found routes are measured only for source-destination pairs for which respective routes were successfully found by all the considered schemes (with the exception of 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 probabilities). We define *probability dilation* as the ratio of the probability of successful reception at the destination of the particular algorithm to that of the shortest path algorithm.

Algorithm	Number of Nodes : 250							
	Density (with 1.4377R Neighbors)							
	6	8	10	20	24	32	40	80
Shortest Path	1	1	1	1	1	1	1	1
EER (NC)	0.082	0.123	0.213	0.470	0.559	0.741	0.829	0.949
I nEPR	0.189	0.202	0.183	0.467	0.552	0.721	0.806	0.939
I Proj Progress	0.186	0.200	0.205	0.474	0.567	0.722	0.805	0.938
nEPR	0.010	0.019	0.024	0.059	0.077	0.114	0.151	0.267
Proj Progress	0.016	0.020	0.030	0.061	0.078	0.119	0.155	0.267
1.4377R Greedy*	1.372	1.381	1.439	26.51	39.5	114.9	351.1	5618.2
1.25R Greedy**	3.155	81.23	86.55	199.8	315	621	951	4329
R Greedy	0	0.023	0.074	0.0438	0.044	0.051	0.062	0.103

* All numbers to multiplied by E-7 ** All numbers to be multiplied by E-6

Fig. 5. Probability of successful reception at destination for different algorithms, $n = 250$.

Algorithm	Number of Nodes : 250							
	Density (with 1.4377 Neighbors)							
	6	8	10	20	24	32	40	80
Shortest Path	100%	100%	100%	100%	100%	100%	100%	100%
EER (NC)	35%	49.6%	73.6%	97.6%	99.6%	100%	100%	100%
I nEPR	38%	52.8%	76.4%	98.4%	100%	100%	100%	100%
I Proj progress	38%	52.2%	76%	98.4%	100%	100%	100%	100%
nEPR	38%	54%	76%	99.2%	100%	100%	100%	100%
Proj Progress	40%	52.4%	73.6%	99.2%	100%	100%	100%	100%
1.4377R Greedy	46%	68%	85.2%	99.6%	100%	100%	100%	100%
1.25R Greedy	12%	29.2%	54%	97.6%	98.4%	100%	100%	100%
R Greedy	0%	1.2%	8.4%	79.6%	87.2%	97.2%	100%	100%

Fig. 6. Success rates, $n = 250$.

The probability dilation measurements are given in Fig. 5 for $n = 250$. The results we obtained give low probability even for the shortest weighted path algorithm (for example 0.00334884, 0.00684035, 0.0302591, 0.361463, 0.467599, 0.64934, 0.761852 and 0.933141 for densities 6, 8, 10, 20, 24, 32, 40 and 80 respectively). Fig. 6 gives the respective success rates of these algorithms. Among the eight localized routing schemes presented, *EER* (NC), *InEPR* and Iterative projection progress schemes performed much better than the other schemes, on probability measure. In 50% of the cases, *EER* (NC) performed slightly better than *InEPR* and Iterative projection progress, contrary to our expectations. For the rest 50%, *InEPR* or Iterative Projection Progresses performed better than *EER* (NC) on the probability measure. The performance difference between these three schemes are very narrow. These three schemes also stayed within reasonable limits to the probability measure achieved by globalized shortest weighted path scheme, which is a significant achievement for localized algorithms.

On success rate measure, *InEPR* and Iterative Projection Progress (also *nEPR* and Projection Progress) performed better than the *EER* (NC) scheme. When compared to the *tR* greedy schemes, all our localized schemes performed better.

Based on the experimental results, we can observe that for sparse networks *InEPR* and *Iterative projection progress* schemes performed best among localized schemes, better than *EER* (NC), while *tR* $-$ *Greedy* methods appear extremely inferior. Therefore *InEPR* and *Iterative projection progress* schemes are good candidates for use with a localized recovery routing scheme to guarantee finding a route.

9. Conclusion

To the best of our knowledge, this is the first study of position based routing in ad hoc network without acknowledgements, with a realistic physical layer. We described several greedy routing algorithms for ad hoc wireless networks, based on realistic physical layer assumptions. These include expected progress schemes, projection progress schemes and the end-to-end routing (NC) protocol.

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 the performance of our localized algorithms is close to the performance of the shortest (weighted) path algorithms, which require global knowledge.

In this article we have studied the case of packet with fixed length. 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 [12]. In [10], 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 [11], 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.

An interesting open problem for future research is the case of end-to-end routing, without hop-by-hop acknowledgement, but with the destination sending an acknowledgement to the source node as a separate routing task. However, we felt that this type of routing, if acknowledgement is really required, is suboptimal to the hop-by-hop acknowledged routing.

We have already explored acknowledgement based Expected Progress routing and hop-by-hop acknowledged, end-to-end routing. Our results are presented in [9]. In [18], we presented a route discovery scheme, *hello* packet protocols for neighbor discovery and the impact of physical layer on routing and broadcasting tasks. We plan to address, in our future research, several problems, including power and cost aware localized routing, adjusting *GFG* routing with guaranteed delivery [4], and route discovery in reactive routing (when received signal strength is measurable, or position information is available) to take into account realistic physical layer. Solution to other problems need also to be reconsidered in the view of physical layer. For instance, our group intends to consider broadcasting problem.

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

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Johnson Kuruvila has 16 years of industry experience in Research, S/W development, Embedded/Distributed System Design and IP Networking/Wireless protocols. Earlier, he was Lead Engineer at AcceLight Networks and Director of Routing/Signaling Platforms at AcceLight Research. He was also Manager of IP Routing system development for the Tera-bit Optera Packet Core project at Nortel Networks. He has been involved with the development of many leading edge products and is a recipient of many performance awards and has given lectures to many product groups in IP Routing Protocols, MPLS/GMPLS signalling and Parallel/Distributed Algorithms. He has given more than 10 invited lectures at various research labs and supervised many graduate and undergraduate research works at various universities. He holds degrees in Electronics/Communication Engineering and Computer Science. He has published many papers and has been awarded two US patents.

Amiya Nayak is an associate Professor at the School of Information Technology and Engineering (SITE) at the University of Ottawa. He received his B. Math. degree in Computer Science from University of Waterloo and Ph.D. in Systems & Computer Engineering from Carleton University, Ottawa in 1982 and 1991, respectively. He has over 15 years of industrial experience in software engineering in avionics and telecommunication applications, working at CMC Electronics and Nortel Networks prior to joining University of Ottawa in 2002. He has been an adjunct research professor at Carleton University since 1994. His research interests are in the areas of fault-tolerant computing, ad hoc networks, and distributed computing.

Ivan Stojmenovic received Ph.D. degree in mathematics in 1985. He held regular or visiting positions in Serbia, Japan, USA, Canada, France and Mexico. He published over 200 different papers in journals and conferences, edited 'Handbook of Wireless Networks and Mobile Computing' (Wiley, 2002), and co-edited 'Mobile Ad Hoc Networking' (IEEE Press, 2004). His current research interests include wireless ad hoc, sensor and cellular networks. He is currently editor of several journals including Journal of Multiple-Valued Logic and Soft Computing, IEEE Transactions on Parallel and Distributed Systems, Parallel Processing Letters, and Parallel Algorithms and Applications. He guest edited recently special issues in several journals including IEEE Computer Magazine (February 2004), IEEE Networks, and Wireless Communications and Mobile Computing.