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Popescu, AM, Salman, N and Kemp, AH (2013) Geographic routing resilient to location errors. IEEE Wireless Communications Letters, 2 (2). 203 - 206. ISSN 2162-2337

https://doi.org/10.1109/WCL.2013.011713.120849

Geographic Routing resilient to Location Errors

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***Abstract*—Geographic routing is an attractive option for large scale wireless sensor networks (WSNs) because of its low overhead and energy expenditure, but is inefficient in realistic localization conditions. Positioning systems are inevitably imprecise because of inexact range measurements and location errors lead to poor performance of geographic routing in terms of packet delivery ratio (PDR) and energy efficiency. This paper proposes a novel, low-complexity, error-resilient geographic routing method, named conditioned mean square error ratio (CMSER) routing, intended to efficiently make use of existing network information and to successfully route packets when localization is inaccurate. Next hop selection is based on the largest distance to destination (minimizing the number of forwarding hops) and on the smallest estimated error figure associated with the measured neighbor coordinates. It is found that CMSER outperforms other basic greedy forwarding techniques employed by algorithms such as most forward within range (MFR), maximum expectation progress (MEP) and least expected distance (LED). Simulation results show that the throughput for CMSER is higher than for other methods, additionally it also reduces the energy wasted on lost packets by keeping their routing paths short.**

***Index Terms*—geographic routing algorithm, position based routing, resilience to location errors, wireless sensor networks**

I. INTRODUCTION

The necessity for energy efficient solutions in wireless sensor networks (WSNs) has materialized in the investigation of geographic routing algorithms for large scale applications [1]. However, the main requirement of position based routing algorithms, that of accurate location knowledge, is an idealistic assumption for their design. Localization solutions have inherent error and, while some are more precise than others, they are typically too expensive to be employed in networks with a large number of nodes. Without the capacity to cope with location inaccuracy, geographic routing algorithms are inefficient in terms of throughput and energy consumption alike [1].

Geographic routing with imprecise location measurements has been investigated by research literature in an attempt to improve its resilience to location errors by increasing the packet delivery ratio (PDR) and minimizing energy consumption [2-6]. Three of the available forwarding techniques stand out [3-5], having different approaches. While [3] and [4] focus on increasing the throughput and make use of the notion of maximum advance towards the destination, proposed by the most forward within range (MFR) routing in [7], [5] aims to optimize power consumption. MFR is considered an energy efficient forwarding strategy when using a fixed transmission power because it minimizes the hop count [3]. However, if the transmission power is adjustable, a different distance metric is needed [5].

The maximum expectation within transmission range (MER) proposed in [3] considers the error probability when making forwarding decisions, determines the goodness of routing candidates and penalizes those whose inaccurate location can lead to packet failure. The routing decision requires knowledge about the furthest neighbor from the transmitting node, but also of the probability that its actual coordinates are within the transmission range (R). It then dismisses those forwarding options with either excessive distance or possibility of backward progress and is prone to choosing the node situated midway between the relays. MER does not cope well with large errors (31.5% of R). [4] uses the objective function named maximum expectation progress (MEP) for positive advance, while backward progress is differently treated. MEP penalizes neighbors only for excessive distance and the protocol can therefore manage larger location errors. The forwarding technique in [4] is used for further improvement by our geographic routing proposal.

The least expected distance (LED) algorithm in [5] is presented as a novel, error-robust routing scheme, whose main aim is to preserve the power saving features of basic geographic forwarding. It is proven in [5] that whichever approach the position-based routing may have, either to optimize the energy spent per hop or for the overall chosen path, the energy-optimal forwarding position is the same. LED determines this theoretical optimum and subsequently chooses as the next hop the neighbor whose real position is closest to it. The algorithm strategically incorporates location error into the forwarding objective function. It is assumed that the estimated coordinates of each node are affected by a Gaussian error of a given variance. As a consequence the erroneous distances between nodes are random variables characterized by the Rice distribution. LED calculates the expectation of the considered distances and chooses the node with the minimum expectation.

Although [3-5] provide solutions for geographic routing in realistic localization scenarios, performance degradation can still be considered severe and can be further reduced. This paper focuses on the comparative study of the various geographic forwarding techniques described above and proposes the conditioned mean square error ratio (CMSER) algorithm as an alternative method to improve the overall performance while still coping with location errors. To be able to compare the routing techniques, all the algorithms are modified to forward with positive progress only, dismissing the possibility of backward progress. Simulations have shown that, under identical circumstances, the PDR of the proposed forwarding method is increased and the energy wasted on lost packets is limited. The CMSER throughput grows higher without the lost packets traveling in the network for a large number of hops, thus reducing the overall power consumption of the network.

The paper is structured as follows: Section 2 describes the assumed mathematical error model. Section 3 presents the investigated routing algorithms and the novel proposal. Section 4 consists in the evaluation of the algorithms through MATLAB simulations. The conclusions are presented in section 5.

II. ERROR MODEL

Network nodes are localized through positioning techniques such as time-of-arrival (ToA) or received signal strength (RSS) [8, 9]. Because the localization process is not accurate, nodes receive the neighbor coordinates with a certain error. Similarly with [3-5], it is considered that the location errors are independent Gaussian random variables and that the error variance of each node is different. Let there be a relay node S_i, with $i = 1, \ldots, I$, where I is the number of transmitting nodes along a routing path. Let F_j be a forwarding candidate of S_i, with $j = 1, \ldots, J$, where J is the number of neighbors of S_i with positive progress to destination D. In the two dimensional plane, S_i and F_j have the real coordinates $S_i\left(x_i, y_i\right)$ and $F_j\left(x_j, y_j\right)$ and the estimated locations $S_i^{'}\left(\hat{x}_i, \hat{y}_i\right)$ and $F_j^{'}\left(\hat{x}_j, \hat{y}_j\right)$, where $\hat{x}_i = x_i + W_i$, $\hat{y}_i = y_i + W_i$, $\hat{x}_j = x_j + W_j$ and $\hat{y}_j = y_j + W_j$. $W_i \sim N\left(0, \sigma_i^2\right)$ and $W_j \sim N\left(0, \sigma_j^2\right)$ are Gaussian random variables with zero mean with standard deviation σ_i and σ_j. For each node, it is considered that the error variance is equal on the x and y axes. The probability density function of the measured distance $\hat{d_{ij}}$ between 2 nodes ($S_i^{'}$and $F_j^{'}$) follows a Rice distribution

$$f\left(\hat{d_{ij}}\right) = \left(\frac{\hat{d_{ij}}}{\sigma_{ij}^2}\right)\exp\left(-\frac{\hat{d_{ij}}^2 + d_{ij}^2}{2\sigma_{ij}^2}\right) I_0\left(\frac{\hat{d_{ij}}\, d_{ij}}{\sigma_{ij}^2}\right). \quad (1)$$

The estimated distance $\hat{d_{ij}}$ is a circularly normal random variable with non-zero mean (2) and d_{ij} is the accurate distance between S_i and F_j (3).

$$\hat{d_{ij}} = \sqrt{\left(\hat{x}_i - \hat{x}_j\right)^2 + \left(\hat{y}_i - \hat{y}_j\right)^2} \quad (2)$$

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \quad (3)$$

I_0 is the modified Bessel function of the first kind and order zero and $\sigma_{ij}^2 = \sigma_i^2 + \sigma_j^2$. The mean (expectation) of the estimated distance $\hat{d_{ij}}$ is

$$E\left(\hat{d}_{ij}\right) = \sigma_{ij}\sqrt{\frac{\pi}{2}}\, L_{\frac{1}{2}}\left(-\frac{d_{ij}^2}{2\sigma_{ij}^2}\right), \quad (4)$$

where $L_{\frac{1}{2}}(x)$ denotes the Laguerre polynomial (5) and I_1 is the modified Bessel function of the first kind and first order.

$$L_{\frac{1}{2}}(x) = \exp\left(\frac{x}{2}\right)\left[\left(1 - x\right) I_0\left(-\frac{x}{2}\right) - x I_1\left(-\frac{x}{2}\right)\right] \quad (5)$$

The variance of the estimated distance $\hat{d_{ij}}$ is

$$Var\left(\hat{d_{ij}}\right) = 2\sigma_{ij}^2 + d_{ij}^2 - \left(\frac{\pi\sigma_{ij}^2}{2}\right) L_{\frac{1}{2}}^2\left(-\frac{d_{ij}^2}{2\sigma_{ij}^2}\right). \quad (6)$$

III. ROUTING ALGORITHM

Location errors have a significant impact on geographic routing performance. In this section we briefly discuss a few forwarding techniques employed by [3-7] and propose a novel routing algorithm to address the presence of location errors. The aim is to minimize the effect of inherent positioning errors on the network throughput, when nodes use a fixed transmission power. To be able to analyze strictly the forwarding techniques, it is assumed that the communication is not affected by the environment.

According to a simple forwarding algorithm like MFR, when a node S_i has to choose among the available forwarding candidates with positive advance, the next hop F_j will be the one closest to the destination D, so the node with the largest distance d_{ij}. However, as underlined in [3], it is likely that the furthest node from S_i will also be the nearest to the edge of R. Because all choices are made based on the estimated distances, the transmission is susceptible to failure and energy wastage. If a statistical error characteristic associated with the measured location of each node (a mean and error variance) is known and communicated along with the coordinates, then the forwarding decision can make use of this data.

The objective functions of MER and MEP compute the expectation of a successful transmission for F_j, based on their statistical error characteristics. To determine the neighbor with the highest expectation within R, both MER and MEP policies use statistics related to point and area coverage, similar to those used in target destruction applications within circular areas. Thus, the probability of the real coordinates of a node to be found within a circle centered at its estimated coordinates is detected. MEP's decision is based on the measured progress to D, expressed as P_{ij}, and on the probability of node F_j to be out of the R of S_i having an "excessive" real distance. The neighbor goodness is determined by calculating their probability to be found within a circular area of a radius M_{ij} (7), where M_{ij} represents the random variable of the Rayleigh cumulative distribution function. MEP is used in our algorithm proposal, but the mathematical approach is different.

$$M_{ij} = R + \sigma_{ij} - \hat{d_{ij}}. \quad (7)$$

We propose that S_i first calculates the mean square error (MSE) associated with all F_j with

$$MSE_{ij} = E\left(\hat{d}_{ij} - d_{ij}\right)^2 = E\left(\hat{d_{ij}}^2\right) - 2d_{ij}E\left(\hat{d_{ij}}\right) + d_{ij}^2, \quad (8)$$

where $E\left(\hat{d_{ij}}\right)$is calculated with (4) and $E\left(\hat{d_{ij}}^2\right)$ is calculated as follows:

$$E\left(\hat{d_{ij}}^2\right) = E(\hat{x}_i^2 - 2\hat{x}_i\hat{x}_j + \hat{x}_j^2) + E(\hat{y}_i^2 - 2\hat{y}_i\hat{y}_j + \hat{y}_j^2) \quad (9)$$

Using the second moments in (9), i.e. $E(\hat{x}_i^2) = x_i^2 + \sigma_i^2$, $E(\hat{y}_i^2) = y_i^2 + \sigma_i^2$, $E(\hat{x}_j^2) = x_j^2 + \sigma_j^2$ and $E(\hat{y}_j^2) = y_j^2 + \sigma_j^2$, we obtain (10)

$$E\left(\hat{d_{ij}}^2\right) = 2\sigma_i^2 + 2\sigma_j^2 + x_i^2 + x_j^2 + y_i^2 + y_j^2 - 2x_ix_j - 2y_iy_j. \quad (10)$$

The actual distance d_{ij} is not available as the accurate locations are unknown, hence the calculations are made using the estimated coordinates instead. The next step is to calculate the mean square error ratio (MSER) associated with each forwarding candidate F_j and to detect the best choice as follows:

$$MSER_{ij} = MSE_{ij}/\hat{d}_{ij}. \tag{11}$$

$$F_j = argmin\ (MSER_{ij}) \tag{12}$$

By choosing the neighbor F_j with the minimum value for MSER (12), a balance is obtained between the shortest distance to D and the smallest error of the next hop. In the special case of 2 forwarding options equally far from S_i, the next hop will be the node with the smallest error. If the error characteristics are the same, the next hop will be the furthest one from S_i. So, F_j is chosen depending on the scale of the error in comparison with the distance.

The algorithm can be further improved by considering that F_j, although optimal from the MSE point of view, can still be close to the edge of R, especially when few routing options are available. The routing selection can be refined by considering a condition similar to that of MEP, but redefined as follows: that the squared difference between R and the estimated distance to the neighbor node should be greater than the variance of the erroneous distance (13). The quadratic form is used to have the same unit of measurement. The inequality in (13) contains the variance of the erroneous distance (6) instead of the standard deviation of each of the nodes (sender and receiver) as in MEP, because the entire algorithm is based on considering the distance between nodes as a random variable. We call this the CMSER algorithm.

$$\left(R - \hat{d_{ij}}\right)^2 > Var\left(\hat{d_{ij}}\right). \tag{13}$$

For a complete comparison and a more appropriate evaluation, the basic forwarding ideas of MEP and LED are used in our study, but with alterations: MEP is simulated with the expression in (13) instead of that in (7), while LED is now based on the maximum $E\left(\hat{d_{ij}}\right)$ used to determine the F_j closest to D, instead of that used for the F_j closest to a predetermined energy-optimal forwarding position.

IV. SIMULATION RESULTS

We analyze, via MATLAB simulation, the PDR of the forwarding methods referred to as MFR, LED, MEP, MSER and CMSER, when the nodes are erroneously localized with σ_i, $\sigma_j \in [0, \sigma_{max}]$. Nodes are randomly distributed over a network area of $200\,m^2$. Several scenarios are studied, as described in table 1, where SE random sensing events take place. Each source sends 1 packet of 1024 bits in the network. The probability of correctly receiving any packet within R is 1, and 0 outside R. Performance is studied for different network densities (when the number of nodes N is varied), for different values of the maximum standard deviation of errors (σ_{max}) or different R. Each scenario consists of a network distribution with accurate node coordinates, where packet forwarding is made with MFR, and a number of η distributions with inaccurate locations (η being the number of iterations), where the errors have been modeled as in section 2. The figures are obtained through averaging over η.

Table I
SIMULATION SCENARIOS

Scenario	N	R(m)	σ_{max}(m) (% of R)	η	SE
1	50-650	40	8 (20%)	500	50
2	350	40	4-20 (10-50%)	100	50
3	200	10-100	5 (50-5%)	300	30

Fig. 1 presents the forwarding performance for different network densities. For an optimal density of more than 200 network nodes, CMSER has a PDR between 70% to 80%. The MFR performs worst with approximately 10% PDR for all network densities. MSER and LED have a similar throughput with PDR values between 20% and 50%. We do notice however that MSER slightly increases its performance for denser networks, above 350 nodes. Looking strictly at MEP we notice an obvious improvement over the other methods, with a parallel behavior to that of CMSER for over 200 nodes, but with a PDR of 50%. Fig. 2 is provided for clarity of view and as a support for the reliability of our simulations. For 500 iterations, it is with a 95% confidence level that the true value of the PDR is in the confidence interval.

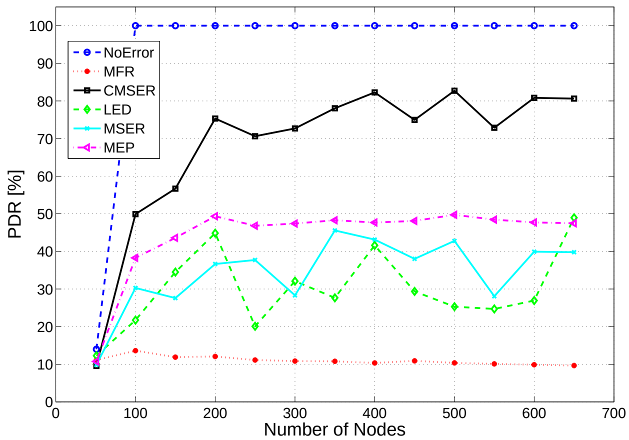

Figure 1. Routing performance for Scenario 1

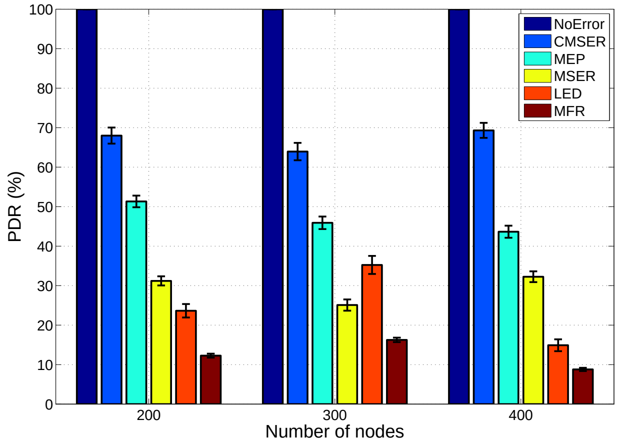

Figure 2. PDR bar chart with confidence intervals

Looking at the PDR when σ_{max} is increased (Fig. 3), the performance degrades, as expected. The most severe performance degradation is that of LED, which for large errors behaves worse than MFR. In this scenario with an optimal network density, MSER outperforms LED, but this is mainly because of LED's severe degradation. MEP has the second best performance maintaining a PDR of above 50% only for errors with σ_{max} up to 10% of R. CMSER is the best forwarding method here because its performance has the least abrupt degradation slope with the increase of errors. Although the PDR for CMSER drops below 50% when σ_{max} is higher than 45% of R, it still maintains a significantly superior performance than for the other methods.

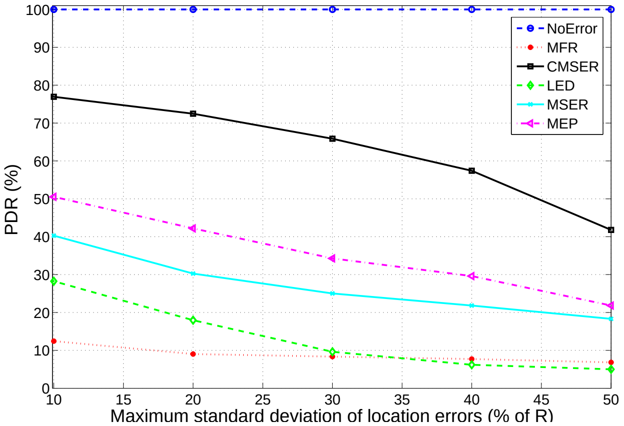

Figure 3. Routing performance for Scenario 2

Varying the R (Fig. 4) within a reasonably dense network increases the potential forwarding options for each node. With more neighbors to choose from, the throughput also increases. For $R \leq 20$, all the considered forwarding methods fail to find neighbors to forward to and the routing fails. While for $R > 30$ CMSER increases its throughput progressively from 60% to almost 100% PDR, none of the other algorithms perform as well. The PDR curve for MFR remains detached below the rest of the algorithms for all values of R.

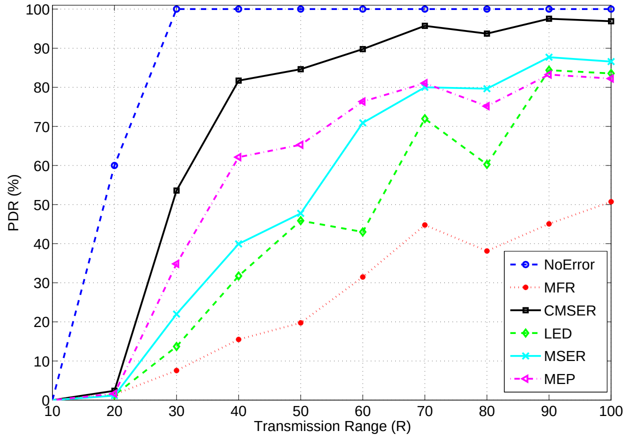

Figure 4. Routing performance for Scenario 3

For scenario 1 we investigate the hop count of the lost packets. Our simulations show path length directly influences the energy consumed without results, which leads to a shorter network lifetime. For a network size less than 200 nodes CMSER has the highest average hop count per lost packet of all the routing methods. For more than 200 nodes, MSER and CMSER have similar hop count for the lost packets, higher than MFR, but lower than LED and MEP. By choosing different forwarding candidates than MFR, with less progress to D, the length of the CMSER paths is slightly increased. This confirms the tradeoff which CMSER has between the PDR and the hop count. However, if we take into consideration the total number of packets lost by each routing algorithm and their number of hops until the moment of loss, CMSER is the least energy wasteful ensuring the longest network lifetime.

V. CONCLUSIONS

Making geographic routing algorithms resilient to location error is imperative as this type of routing is energy efficient and very suitable to large scale networks. This paper proposes a novel routing algorithm, CMSER, whose performance in terms of throughput is considerably better when compared to other basic greedy routing techniques such as those employed by MFR, MSER, MEP and LED. The MATLAB simulations used in this study refer to three scenarios in which the PDR is analyzed under different network sizes, error characteristics and communication ranges. All results confirm that CMSER outperforms other algorithms when the network objective is to increase packet delivery. Overall energy costs are also kept down to a minimum. CMSER makes use of the notion of maximum progress to destination, but gives more importance to the probability of success when coordinates are affected by location error. As a consequence, the energy spent on lost routing packets is considerably decreased. While the paths of the received packets of CMSER may be longer, the routes of the lost packets are kept short, being surpassed only by MFR, which does not cope with location error at all.

REFERENCES

[1] A. M. Popescu, I. G. Tudorache, A. H. Kemp, Surveying Position Based Routing Protocols for Wireless Sensor and Ad-hoc Networks, International Journal of Communication Networks and Information Security 4 (1) (2012)

[2] Y. Kong, Y. Kwon, J. Shin, G. Park, Localization and dynamic link detection for geographic routing in non-line-of-sight (NLOS) environments, EURASIP Journal on Wireless Communications and Networking (2011)

[3] S. Kwon, N.B. Shroff, Geographic routing in the presence of location errors, Computer Networks 50 (2006) 2902-2917

[4] R. Marin-Perez, P.M. Ruiz, Effective Geographic Routing in Wireless Networks with Inaccurate Location Information, In Proceedings of the 10th International conference on Ad-hoc, mobile, and wireless networks (ADHOC-NOW'11), Hannes Frey, Xu Li, and Stefan Ruehrup (Eds.). Springer-Verlag, Berlin, Heidelberg, 1-14.

[5] B. Peng, A.H. Kemp, Energy-efficient geographic routing in the presence of location errors, Computer Networks 55 (2011) 856-872

[6] A. M. Popescu, N. Salman, A. H. Kemp, Energy Consumption of Geographic Routing with Realistic Localization, IET Networks 1 (3) (2012) 126-135

[7] H. Takagi, L. Kleinrock, Optimal transmission range for randomly distributed packet radio terminals, IEEE Transactions on Communications 32 (3) (1984) 246-257

[8] N. Salman, H. K. Maheshwari, A. H. Kemp, M. Ghogho, Effects of anchor placement on mean-CRB for localization, The 10th IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net) (2011) 115-118

[9] N. Salman, M. Ghogho, A. H. Kemp, On the Joint Estimation of the RSS-Based Location and Path-Loss Exponent, IEEE Wireless Communications Letters 1 (1) (2012) 34-37