Enhanced Localization in Wireless Ad Hoc Networks through Cooperation

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Abstract. Next generation networks consider context information to deliver personalized services, where this context can include positioning information. On the other side, positioning information is relevant to some of the network main functions: geographical routing, network coverage, enhanced security, power saving etc. Therefore determining the position of nodes in wireless networks is pivotal and this paper proposes a cooperative iterative framework to expand the overall localization coverage in an ad hoc wireless network.

Keywords: Positioning, Ad hoc, distance estimation, cooperation.

1 Introduction

All-encompassing wireless networks need to provide personalized services to the end user, guaranteeing overall service availability in a highly dynamic environment. Some of those value added services are delivering specific information to the users relevant to their current locations. The position information of mobile nodes in wireless networks can support location-aware applications (e.g. location-based services like mobile commerce, location based advertising, social networking, tracking, monitoring) to offer flexible and adaptive personal services, but can also improve the network performance through location-based routing, load balancing and coverage management. Radio spectrum and terminal battery are the main constraints in wireless communications. For an efficient use of all the available resources, the position information will help to predict the required resources even in heavily loaded networks.

A straight forward example for the benefit of positioning information for location based radio resource management is shown on Fig 1. We consider a scenario where more than one wireless network provides coverage (in this example Beyond 3G or 4G RAN cell and a WLAN hotspot). The idea is to select one of these networks based on its service, capacity and current load, taking into account user's location and mobility information [1]. If the mobile terminal (MT) is moving slowly along the trajectory, it is reasonable to hand over to a small hot-spot cell, which locally provides significantly higher data rates than the Radio Access Networks (RAN) cells do. For a high MT speed along the trajectory, the time that the user resides in the hot-spot cell area is so short, that the effort for a handover exceeds the achievable gain in data rate. In such a case it does not bring any benefit to hand over to the WLAN hotspot. It is preferred to stay connected to the previous RAN cell (BS1) or hand over directly to BS3.

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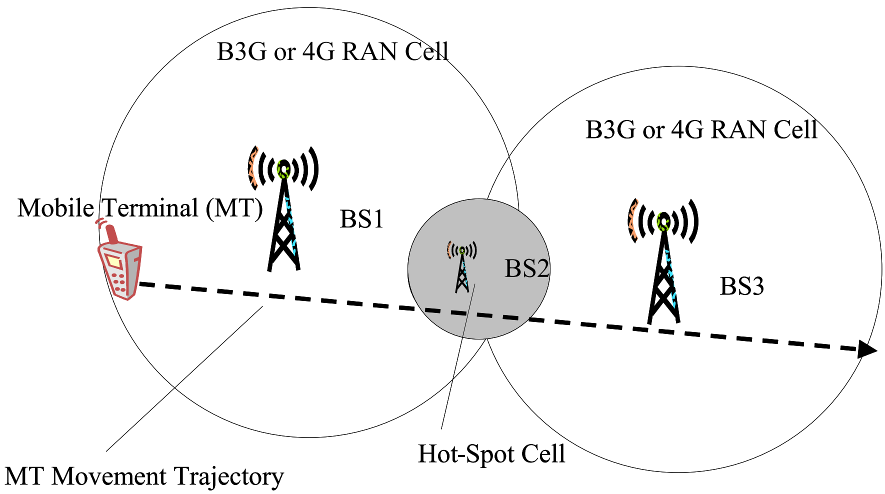

Fig. 1. Location based handover

Global Positioning System (GPS) is the most widely used positioning system. However, it cannot be deployed indoors because of the absence of line of sight transmission between satellite and receiver. GPS receivers are costly and power consuming, which makes them unsuitable in dense ad hoc networks with strict energy constraints. Furthermore, the typical error values for GPS positioning (3-30m) are not tolerable for dense sensor networks. Thus, development of other solutions for indoor scenarios is necessary. In this paper we consider positioning algorithms in ad hoc networks.

Unlike infrastructured networks, ad hoc networks cannot rely on dedicated infrastructure to forward traffic across fixed network segments between mobile users. Furthermore, direct communication between all nodes is infeasible due to limited transmission range. The nodes have to establish multi-hop wireless paths and to cooperate in order to dynamically maintain routes. Cooperation between nodes is essential also for localization, because it allows nodes which are not in range of a sufficient number of references (and therefore at the first sight not able to be localized) to be located. In a two-dimensional space, at least three references are required to estimate a node's position. Given a limited range, it is very unlikely that a node will be able to directly communicate with a sufficient number of references and estimate its position.

The rest of the paper is organized as follows: the next section describes the key aspects of cooperative localization. Section 3 gives an overview on the state of the art in the area of interest. In section 4 we present our approach to design a new algorithm. The last section, section 5, concludes the paper.

2 Cooperative Positioning

The availability of position information depends on the existing infrastructure, such as GPS satellites or cellular base stations. Cooperative positioning techniques are used in scenarios where non-cooperative (single-hop) solutions are not feasible, or do not perform well in terms of accuracy, availability, cost and complexity. Especially in indoor scenarios, where a line of sight connection to reference nodes is not always available, the mobile terminal can benefit from cooperative positioning in order to obtain information of its own location. Typically, algorithms assume a number of location-aware nodes, called *anchors*. They may have obtained their positions through GPS or by some other means. Those nodes are used as references for the other, unknown nodes to estimate their positions. Generally, the localization process is divided in two phases. The first phase is the ranging phase, where nodes estimate the distances to their neighbors. In the second phase, the ranging information is used for calculation of unknown nodes' coordinates. Optionally, there might be a third phase where the positions are refined through an iterative procedure for further accuracy improvement.

2.1 Ranging Phase

Range measurements can be based on Received Signal Strength (RSS), Time of Arrival (ToA) or Angle of Arrival (AoA). ToA based distance estimation is relying an the fact that radio waves propagate at the speed of light, and knowing the time a signal needs to propagate from one node to another, we can easily obtain the distance between them. Accurate estimates are feasible in line of sight conditions. In order to accurately measure the time of propagation, sender and receiver have to be perfectly synchronized, and therefore fast processing capabilities are needed. One way to avoid the need of precise synchronization is to measure the round trip time (RTT) from transmitter to receiver and back. However, it is still difficult to extract the exact processing and delay time in the receiver. In short range scenarios this value cannot be ignored, as it is in order of transmission time. AoA techniques use antenna arrays to measure the angle at which the signal arrives, but require additional hardware which is costly and needs to be maintained. RSS based methods estimate the distance between sender and receiver by measuring the attenuation in radio signal strength, and considering the appropriate propagation model. In an indoor scenario usually a log-normal shadowing model is being used. The benefit of RSS based location methods is its simplicity and availability regardless the radio access network, as well as the fact that RSS of radio signals is being measured during data communication, to decide whether the packet transmission has been successful or not. There is no additional bandwidth or energy required to perform signal strength measurements. Nevertheless, the performance of these techniques depends on the model used to find the relationship between measured RSS and distance. Moreover, there exist several hybrid approaches that exploit a combination of the aforementioned techniques to enhance localization accuracy and to minimize the number of required reference nodes. Once the distances to a sufficient number of anchors are obtained, a node has to perform a trilateration/multilateration algorithm to compute its coordinates.

2.2 Position Estimation

Lateration uses the geometric properties to estimate the target location. Each estimated distance represents the radius of a circle centered at the corresponding reference node. For 2-D positioning, measurements from at least three reference nodes are

Fig. 2. Trilateration

required, and the location is obtained as the intersection of circles, as represented on Fig. 2.

Having in mind the errors in estimated distances to the anchors, the geometrical trilateration technique can only provide a region of uncertainty [2] instead of a single point. Therefore the solution is based on iterative algorithms to obtain the node position by formulating and solving a set of nonlinear equations. Due to nonlinearity, to find a solution for a (n-1)-dimensional system, n equations are required. Least Squares (LS) algorithm is used in order to minimize the error between the estimated and the real position. In general, linear LS estimation is a suboptimal positioning technique. However, it has been shown in [3] that it performs similar to the nonlinear ones, especially for small noise variances. Besides that, the computational complexity is significantly lower in linear LS methods. In [4] both linear and nonlinear LS methods for position estimates via trilateration are presented. When distances to more than three reference nodes are available, the technique of position calculation is called multilateration. Here, a position estimate is calculated by reducing the difference between actual distances between node i and node j, and estimated distances d_{ij}. The difference is given by:

$$f_{ij}(x,y) = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} - d_{ij} . \tag{1}$$

For n distance estimates, the position of the unknown node is obtained by minimizing the function

$$F(x,y) = \sum_{i=1}^{n} f_i(x,y)^2 . \tag{2}$$

2.3 Key Aspects of Cooperative Localization

The main sources of error are measurement errors in the ranging phase, and iterative error accumulation during the second phase. The ranging errors arise due to multipath and shadowing effects. The algorithm should be distributed rather than centralized, meaning it should not depend on one single central point responsible for all computations, due to the infrastructureless nature of ad hoc networks. Additionally, by using decentralized approach the algorithm is tolerant to node failure. To deal with energy constraints, computation and communication overhead should be minimized to save the nodes' battery lifetime. Having in mind that the nodes are in general mobile, the response time should be low, so the localization system can be easily updated every time the topology changes. The algorithm has to provide accurate position estimates, whereby the level of accuracy depends on the application.

Performance parameters are mainly accuracy and latency. Ability to provide low latency is especially important in dynamic scenarios where a low response time is crucial. The two major cost parameters are the amount of communication between nodes, and the computation process in the nodes. Cooperative solutions have to achieve desired cost-performance trade-offs. The number of actively participating nodes should be kept to a minimum, and therefore an appropriate cooperation subset has to be chosen, while the other nodes can be ignored. Such a restrictive and selective use of references is crucial in networks with limited resources.

3 Related Work

In multi-hop scenarios, localization algorithms can be range–based or connectivity-based (also called range-free) [5]. In range-based approaches distance estimates are usually obtained using one of the previously described techniques (TOA, AOA, RSSI). In [6] it has been shown that in multi-hop networks, while increasing the number of hops for a fixed source to destination distance, the accuracy deteriorates for TOA-based systems. In contrast, for RSSI-based systems the accuracy improves. However, most range-based approaches are not suitable for low density networks, since the large distance between nodes does not permit to perform a sufficient number of range measurements. For sparse sensor networks the most widely used technique is multi-dimensional scaling (MDS), a statistical dimensionality reduction technique for data analysis that uses pair-wise distance measurements as input data [7], [8].

On the other hand, range-free algorithms are based on connectivity information among nodes. Two sensors being in range define a proximity constraint, which can be exploited for localization. These approaches do not assume any additional hardware functionality, as they do not rely on distance measurements. Therefore, their main advantage is its simplicity and low cost. In the "Ad Hoc Positioning System (APS)" algorithm developed by Niculescu and Nath [9] anchors flood the network with their locations. The proposed scheme is known in literature as DV (distance vector)-hop. Hops are being counted along the shortest path between any two anchors, to estimate the average distance of one hop. The average hop length is spread through the network as the correction factor. After receiving the correction factor, every node is able to estimate its distance to the anchors and to perform trilateration. The algorithm is completely ad hoc, and does not depend on measurement errors. Simulation results showed the mean positioning error of 45% transmission range.

An extension is the "DV-distance" approach, proposed in [9] where the measured distance is propagated among neighboring nodes instead of hop count. DV-distance is a range-based distributed localization algorithm, using RSS measurements. Performance is comparable to DV-hop, although the method is sensitive to measurement errors. Two similar approaches are the "hop-terrain" algorithm developed by Savarese and Raabey [10], and the "AHLoS" (Ad Hoc Localization System) scheme of Savvides et all [11]. The algorithm proposed in [10] is separated into two phases: start-up and refinement. In the first phase an algorithm similar to DV-hop is used to obtain an initial estimate of node locations. The refinement algorithm is run iteratively afterwards. At each iteration step, all nodes update their location estimates by least squares trilateration, taking into account only nodes within one-hop neighborhood. Refinement stops when, after a number of iterations, the position update becomes small and it reports the final position. It was shown in simulations that the algorithm achieves average position errors of less than 33% of a node's transmission range, when at least 5% of nodes are anchor nodes and the average number of one-hop neighbors is greater than 7 nodes.

AHLoS algorithm [11] uses TOA as the primary ranging method, and multilateration as the basis for position calculation. It follows an iterative scheme: once an unknown node estimates its position, it becomes an anchor and broadcasts its position estimate to all neighboring nodes. The process is repeated until all nodes that can have three or more reference nodes obtain a position estimate (Fig. 3). A drawback of iterative multilateration scheme is the error accumulation that results from the use of estimated locations as anchors. In [12] the authors proposed an iterative algorithm that takes into account the behavior of the channel to provide accurate indoor positioning and importantly reduce error propagation. Simulations showed that inaccurate ranging has a bigger impact on error propagation than the use of estimated (and therefore erroneous) locations as anchors.

Fig. 3. Iterative multilateration

Some algorithms do not perform well in low density networks, for instance those that depend on distance measurements when the transmission range is short. One example is the AHLoS algorithm proposed in [11] that requires a high degree of node connectivity. The percentage of required reference node decreases as the network density increases. A comparison performed in [13] showed that DV-hop requires a minimum connectivity. The refinement procedures are extremely costly in terms of communication overhead since they take many iterations before convergence.

4 Proposed Cooperative Positioning Framework

Aspects that have to be considered when choosing or designing an ad hoc positioning algorithm are limited resources, number and density of nodes, percentage of anchors and network topology. It is also important to choose the appropriate range measurement method for the environment of interest. For example, in high-density sensor networks the most valuable ranging technique is RSS [14]. Limited resources refer mainly to energy constraints in an ad hoc network. The battery lifetime is usually limited, and nodes have low processing capacity. Therefore it is important to have an even distribution of power consumption among nodes, and a distributed approach generally solves this issue. In a purely ad hoc network, not depending on a central server or infrastructure, all of the entities have the same capabilities. The number of actively participating nodes should be kept to a minimum, and therefore a proper cooperation subset has to be selected, while the other links can be discarded.

We propose one algorithm based on iterative multilateration, which provides a way to expand the network coverage in a step-by-step fashion. In this sense, coverage is the fraction of nodes that have an accurate position estimate. We assume a middle-scale ad hoc scenario with a certain percentage of anchor nodes. Specifically, in our simulations we consider 30 nodes, from which 6 are anchor nodes and 24 are unknown nodes. The nodes are placed in a 30m x 30m grid, and transmission range is set to 10 m and 15 m, respectively.

Once a node joins the network, it has to perform some sensing to identify which nodes are in its range. During this network discovery phase, signal strength is being measured to decide whether the packet has been received successfully or not. Therefore we decided to use RSS measurements for distance estimation. We use the log-normal shadowing propagation model, with typical parameters for indoor environment. General expression for this propagation model is:

$$RSS_d = 10\log_{10} P_r = 10\log_{10} P_t - 10\beta \log_{10} \frac{d}{d_o} + X_\sigma , \tag{3}$$

where P_t is the transmitted power, d is the distance between transmitter and receiver, d_o is the reference distance (usually 1m), β is the path loss exponent and X_σ is a zero-mean Gaussian random variable with standard deviation σ, representing the shadow fading component. Typical parameter values for an indoor scenario are $\beta = 3$ and $\sigma = 7$. Once the distances to a sufficient number of anchors are obtained, a node has to perform a trilateration/multilateration algorithm to compute its coordinates. In order to enable 2-D positioning, distances to at least three reference points must be available.

If we integrate message exchanges into routing protocols, location discovery is almost free in terms of communication cost. To choose the nodes most suitable for cooperation, we suggest to associate a utility function to the scenario, as a function of all metrics relevant for the positioning algorithm. This function contains useful information, i.e. which nodes are in range of each other, how is the quality of links between them etc. 'Quality of link' parameter is a representation of the channel condition between two nodes in an ad-hoc environment. It helps to establish a statistical measure of the node-to-anchor channel conditions. To assess the quality of links, we perform 100 RSS measurements, and take the statistical mean and standard deviation. Those sets of measurements, related to specific anchor nodes, with a smaller standard deviation are considered to have better quality, and will have a priority in the reference nodes selection phase.

Once the suitable anchor nodes are chosen and the distances to at least three anchors are estimated, position is calculated using least squares. In the first iteration, a node uses anchors as references, and once it calculates its own position, it becomes a new anchor, but with some uncertainty associated with it. This uncertainty of estimate will also be included in the utility function as a metric for reference selection. According to [12], the quality of links is more important for anchor selection than quality of estimate, and therefore it should have a higher priority as part of the utility function. The framework description is given in the following diagram:

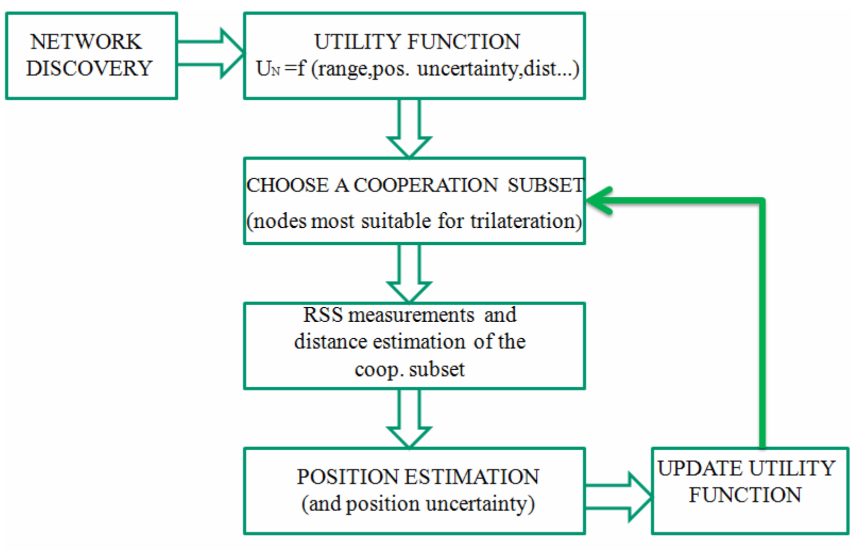

Fig. 4. Iterative cooperative positioning algorithm

Every newly estimated position acts as a reference point for its neighborhood and extends system coverage. To decide whether or not a new estimate can advertise itself as an anchor, we need to set an error threshold. Threshold adjustment makes it possible to find a trade-off between desired accuracy and number of iterations needed for full coverage. It is evident that communication range will have an impact on coverage. Fig. 5 shows that for a larger range it will be possible to incorporate more new anchors after the first iteration.

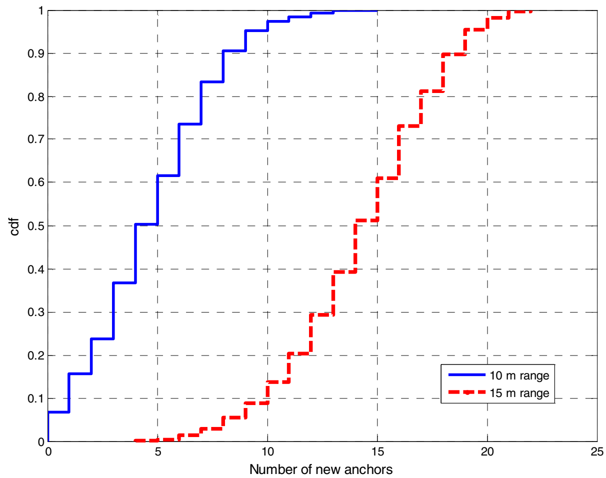

Fig. 5. Number of newly incorporated anchors after first iteration

Fig. 6 plots the error cumulative distribution function (cdf) for transmission range values 10 m and 15 m, respectively.

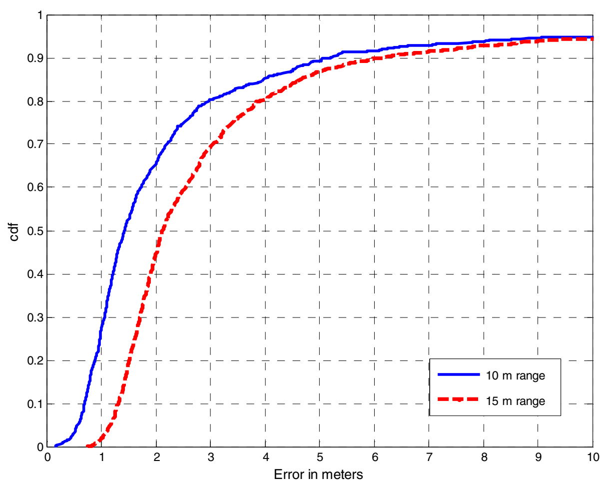

Fig. 6. Error probability

In general, when we set a higher transmission range, the error value (in meters) increases. All these errors contribute to error propagation in subsequent iterations. If the application allows us to use less accurate position estimates, full coverage will be achieved faster. In that case less number of iterations are required; communication overhead is significantly reduced as well as the computation/processing costs. The main goal is to identify the optimum threshold for a certain application and the required accuracy.

5 Conclusion

Cooperative positioning has received broad significant interest, from the robotics, optimization, and wireless communications communities [5]-[13]. While positioning and navigation have a long history, the challenge is to allow nodes which are out of range of any known reference locations to become aware of its location through cooperation, and hereby increase localization performance in terms of both accuracy and coverage. We propose an interactive cooperative positioning framework as a first step towards a distributed solution and able to adapt to a variety of scenarios. This solution provides a way to expand the network coverage in a step-by step fashion by exploiting the localization of known nodes, and future work will address further the application of Utility functions as a means of identifying the most useful nodes to form a member of the cooperative subset for enhancing positioning accuracy.

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