A MOBILE-BASED LOCALIZATION SYSTEM FOR INFRASTRUCTURE-INDEPENDENT EMERGENCY COMMUNICATION

HOJAT BEHROOZ and MOHAMMAD ILBEIGI

Dept of Civil, Environmental, and Ocean Engineering, Stevens Institute of Technology, Hoboken, USA

After natural or human-made disasters, determining the locations of individuals needing urgent assistance is critical and time-sensitive. This paper introduces a novel ad-hoc infrastructure-less communication system for emergency scenarios, relying solely on basic mobile device capabilities. The proposed approach estimates mobile device coordination using multilateration, incorporating path loss theory to transform receiving signal strength into distance. A least square optimization algorithm is also applied to enhance localization accuracy. The system facilitates coordination and communication among citizens and first responders by strategically positioning a few emergency mobile devices as temporary base stations. Mobile devices search for neighboring base stations and transform into temporary base stations upon finding at least four. Those temporary base stations assist farther mobile devices in localization, creating a cascading effect until no more mobile devices are discovered. Simulation demonstrates robustness with a 97% discovery rate, maintaining accuracy even in environmental noise. While promising, real-world validation is essential to assess performance under diverse conditions and practical feasibility.

Keywords: Rescue operation, Mobile ad hoc network, Trilateration/multilateration, Path loss theory, Least square optimization, Levenberg-Marquardt, Received signal strength.

1 INTRODUCTION

Telecommunication infrastructures have long been the backbone of emergency management, providing crucial connectivity among citizens, first responders, and authorities in the aftermath of disasters (Khan et al. 2020). Right after a natural or human-made disaster, one of the most time-sensitive and critical tasks is accurately determining the locations of individuals requiring urgent assistance. Yet, large-scale disasters, including earthquakes, hurricanes, and man-made catastrophes, can obliterate these vital telecommunication networks, hampering rescue efforts for extended periods (Hansson et al. 2020). Temporary solutions have emerged to address the challenge of maintaining communication when traditional infrastructures falter (Bushnaq et al. 2021, Sheikh et al. 2022). However, these technologies rely on costly equipment that is not universally accessible, and their deployment can be time-consuming, often taking several days.

To address those issues, Ilbeigi et al. (2022) proposed a framework to automatically establish a decentralized ad hoc mobile network in which citizens' cell phones connect with nearby devices via WiFi Direct through a mobile application to maintain an identical ledger containing all devices' spatial information found through their GPS. Nonetheless, their proposed framework relies on features such as the GPS systems of mobile devices, WiFi Direct technology, and mobile
applications, which are primarily accessible on more advanced smartphones, require execution of an application, and the activation of WiFi Direct by citizens. It also depends on the accuracy of GPS localization, which is often compromised and unavailable (Kaplan and Hegarty 2017). On top of those obstacles, the availability of mobile devices is fundamentally contingent on their power source, primarily the battery. However, the battery capacity is finite, making power consumption management critical, especially in emergencies where recharging the battery may not be feasible (Carroll and Heiser 2010). To address those issues, this study aims to create a novel communication system that relies solely on fundamental mobile device communication capabilities to establish decentralized and infrastructure-independent communication during emergencies. The proposed model strategically places at least four Emergency Mobile Devices (EMDs) as base stations. When a mobile device successfully detects a few base stations, it transmits a message containing its Received Signal Strength (RSS). Later, this RSS is converted to distance using radio frequency principles. If a mobile device identifies at least four neighboring base stations, it undergoes accurate coordination through trilateration/multilateration, transforming into a temporary base station. This transformation allows further mobile devices to discover the temporary base station for enhanced localization. All RSS data are exchanged between mobile devices and neighbors through a multi-hop message-passing system. Those messages are finally directed to an EMD as a consolidator for localization.

In the subsequent sections, we briefly explore fundamental principles in cellular communication systems and their relevance to emergency management. We delve into the potential applications of radio frequency propagation properties for distance measurement, aligning with the goals of our study. The framework and its key components are then outlined. The paper concludes with a presentation of the outcomes from an extensive simulation and suggestions for future research directions.

2 METHOD

Wireless cellular communication relies on a network of cells served by base stations with specific frequency bands, protocols, and standards to provide services. A wireless cellular network is divided into cells, each served by a base station. Base stations come in various types, from Macro Cells (ranging from a few miles to tens of miles) to small base stations (ranging from 10 meters to 200 meters) (Claussen et al. 2008). A base station periodically emits beacon signals that contain RSS at reference distance (RSS0). Radio signals weaken as they travel over distances, and obstacles like buildings, trees, and vehicles accelerate this signal degradation. The Obstruction factor responsible for environmental signal degradation is quantified by a parameter known as the path loss exponent (\( \nu \)). A mobile device listens to neighboring base stations' beacon signals and measures its RSS. A mobile device's proximity to the base station can be estimated by analyzing RSS. As the base stations are already coordinated precisely, the mobile devices that can discover at least three base stations and evaluate their distance from them can be coordinated through the trilateration/multilateration process. However, the path loss exponent significantly influences the accuracy of distance estimation from RSS. Therefore, the path loss exponent should also be estimated as part of the parameter estimation process, contributing to more precise coordination determination. To achieve precise localization, a minimum of four base stations must be discovered, and simultaneous estimation of the path loss exponent is essential. If the number of discovered base stations (\( n \)) is more than four, while this can enhance the accuracy of estimated parameters, it leads to an overdetermined system of equations. This study’s approach involves formulating an optimization problem and utilizing the Levenberg-Marquardt (Moré 1997) method.
to address the situation. The method is particularly beneficial for solving overdetermined problems, combining aspects of gradient descent and Gauss-Newton methods to find the optimal solution.

A mobile device can estimate the path loss at the reference distance \( \text{RSS}_0 = (PL)(r_0) \) in a wireless communication system through information provided by the base station. It relies on Path Loss formulas (Figel et al. 1969) to estimate RSS based on distance in mobile communication systems. The average path loss for a given transmitter-receiver separation can be expressed as a function of distance \( (\text{RSS} = (PL)(r)) \), utilizing a path loss exponent as presented in Eq. (1).

\[
(PL)(r) = (PL)(r_0) + 10v \log \frac{r}{r_0}
\]

By assuming the reference distance \( r_0 = 1 \) m, the distance between a base station and a mobile station \( (r) \) would be a function of \( v \) as presented in Eq. (2).

\[
r(v) = 10^\left(\frac{\text{RSS} - \text{RSS}_0}{10v}\right)
\]

This proposal empowers mobile devices to operate as miniature base stations. It envisions a scenario where, during an emergency, all mobile communication infrastructure, including base stations, becomes unavailable in the affected area. Consequently, mobile devices lose network coverage and communication capabilities while unsuccessfully seeking to discover surrounding base stations. In response, the authorities define the impacted region by reinstating lost base stations in collaboration with mobile service providers. Then, emergency responders deploy at least four individuals equipped with special EMDs (EMD0, EMD1, ... and EMDn). These EMDs are mobile devices that can function as small base stations, offering coverage up to 100 meters. EMDs are equipped with backhaul communication services (i.e., satellite communication) for inter-device communication. They also incorporate GPS functionality for self-precise localization. Any mobile device possesses a unique identification called the International Mobile Equipment Identity.

This proposal introduces two additional parameters to the base station's essential information broadcasting: an 'Emergency Situation' flag, typically set to 'False' but activated as 'True' during an emergency, and a 'HOP' parameter indicating the distance (measured in the number of hops) between a mobile device and the nearest EMD. EMDs retain a 'HOP' parameter, initially set to zero, and an 'Emergency Situation' flag set to 'True'. Mobile devices within the EMDs' coverage area detect the 'Emergency Situation' flag, indicating an ongoing emergency, and subsequently, they follow a dedicated emergency procedure outlined in Fig. 1.

Mobile devices leverage coordinated EMDs to estimate their RSSs and calculate their distances. Trilateration/multilateration is then applied to convert these distances into new coordinates for mobile devices, leading to a propagation-like process. This process evaluates received messages in EMD0 to categorize mobile devices into five categories: undiscovered, partially discovered I, partially discovered II, discovered, and accurately discovered, as presented in Fig. 2.

Approximating distance measurements \( (r) \) from multiple base stations enables the determination of the mobile device's location in terms of \( (x, y) \) through the trilateration/multilateration method. The method requires two setups for defining equations: 1) Defining measurements represent the distances between the mobile device and the BSs (i.e., \( r_1(v), r_2(v), \ldots, \text{and } r_n(v) \)); 2) positioning and path loss exponent \( (v) \) (i.e., \( x, y, v \)) of at least four BSs (i.e., \( (x_1, y_1, v_1), (x_2, y_2, v_2), \ldots, \text{and } (x_n, y_n, v_n) \)). As the trilateration/multilateration equations follow a quadratic format, it needs at least four equations to estimate three independent variables \( (x, y, v) \). Furthermore, if there were more than four equations (i.e., base stations), this would result in an overdetermined system of equations (Gentle 1998), which can lead to no exact solution. In this
situation, it should seek the best possible solution through methods like least squares optimization techniques (Sauer 2006). Levenberg-Marquardt optimization algorithm is applied to effectively estimate the mobile device position and find the best-fitting solution in an over-determined system of equations by using an optimization technique for solving nonlinear least squares problems. The optimization process involves the following steps.

![Flowchart]

**Fig. 1.** The algorithm that would be executed on all devices in case of emergency.

![Diagram]

**Fig. 2.** BS1, BS2, BS3, and BS4 are temporary base stations. The number of neighboring BSs are: (a) One, (b) Two, (c) Three, and (d) Four.
First, express the equations that relate the known parameters to the independent variables \((x, y, \nu)\) representing the mobile device. These equations include the discrepancies between the estimated distances to the base stations and the actual distances to the base stations, accounting for measurement residual \(e(x, y, \nu)\). Then \(E(x, y, \nu)\) is a column vector of residual takes the Eq. (3) form, where \((x_i, y_i)\) is mobile device coordination of the base station \(i\), and \(RSS_i\) and \(RSS_0\) are received signals for base station \(i\), and \(n\) is the number of base stations.

\[
E(x, y, \nu) = \left\{ e_i(x, y, \nu) = \sqrt{(x - x_i)^2 + (y - y_i)^2} - 10^{\nu \frac{(RSS_i - RSS_0)}{10}} \right\} \quad (3)
\]

Second, an objective function to minimize the sum of squared residual is defined in Eq. (4).

\[
f(x, y, \nu) = \min_{(x, y, \nu)} \frac{1}{n} \sum_{i=1}^{n} e_i^2(x, y, \nu) \quad (4)
\]

Finally, by applying the Levenberg-Marquardt method, the best \((x, y, \nu)\) values for a mobile device that minimizes objective function \(f(x, y, \nu)\) is estimated. The Levenberg-Marquardt method combines elements of gradient descent and the Gauss-Newton method for optimization. The method starts with an initial guess for the dependent variables, denoted as \(X^0 = (x^0, y^0, \nu^0)\). Additionally, a regularization parameter \(\lambda\) is initialized (i.e., \(\lambda = 0.01\)). The method initially needs to estimate an \(n \times 3\) matrix \(A\), which represents the matrix of partial derivatives of the error functions of \(e(x, y, \nu)\) with respect to each variable \(x, y, \nu\) as the Jacobian matrix (Bellman 1997).

The Jacobian matrix \(A\) and the residual vector \(E(X)\) will be used in the Eq. (5) to estimate \(d^k\). \(d^k\) represents an adjustment step that should apply to \(X^k\) to approach the solution. In Eq. (5), \(\text{diag}(A^T A)\) refers to the diagonal elements of the \((A^T A)\) matrix.

\[
d^k = -(A^T A + \lambda \text{diag}(A^T A))^{-1} A^T E(X^k) \quad (5)
\]

By applying the current \(X^k\) value to the above formula, a step value \(d^k\) will be calculated for the next iteration \((X^{k+1} = X^k + d^k)\). This iterative process involves a matrix inversion. To be more flexible, a popular regularization technique, the Moore-Penrose pseudo-inverse (Barata and Hussein 2012), is used whenever the inverse matrix is unavailable. As a stopping criterion, the objective function \(f(x, y, \nu)\) is evaluated during iterations and if the value does not improve after several iterations, the process stops. While this strategy enhances coordination accuracy, it confines the potential for coordinating more mobile devices.

3 EXPERIMENT AND RESULTS

To evaluate the proposed method, a simulation technique was employed. It involved distributing 1,000 mobile devices uniformly within a 250-meter radius, with four EMDs strategically placed, each covering a radius of 100 meters. Mobile devices were assumed to have a coverage range between 10 to 50 meters based on their signal propagation power. Mobile devices incorporated a 5% white noise into the received signal strength. Through the simulation, after 11 rounds of mobile devices transforming into base stations, 977 were accurately discovered and transformed, three were partially discovered, and 20 remained undiscovered. The cost function of discovered mobile devices had a mean of 0.1 and a standard deviation of 0.11. The results demonstrate a remarkable coordination accuracy of 97.7% despite the introduced noise reflecting the environmental impact on distance estimation.
4 CONCLUSION

In conclusion, leveraging basic mobile device capabilities, the proposed method proves effective in emergencies by strategically utilizing EMDs as temporary base stations. Simulation results showcase robustness, achieving high accuracy despite environmental noise. This infrastructure-less approach presents a promising solution for decentralized emergency communication, offering reliable coordination without traditional infrastructure dependence. However, considering real-world environmental variations, the model's applicability requires further experimental exploration. The transformation of mobile devices into base stations needs practical validation, and future work involves real-world experiments to address these challenges and enhance the model's performance.

References