

Retaining Connectivity In Mobile Communication Mesh Networks

Alessandro Pisano* Mauro Franceschelli* Alessandro Pilloni*
Yuri Shtessel** Elio Usai*

* *Department of Electrical and Electronic Engineering, University of Cagliari, Piazza D'Armi, 09123 Cagliari, Italy (e-mail: pisano@diee.unica.it).*

** *Department of Electrical and Computer Engineering, The University of Alabama in Huntsville, Huntsville, Alabama (US) (e-mail: shtessy@uah.edu)*

Abstract: This paper deals with the problem of retaining the connectivity in a Mobile Ad-hoc communication mesh Network (MANET). A multi-agent systems perspective is taken, where primary mobile agents (PAs) can only communicate when the relative distance is less than a “visibility range”. PAs form a network that can become disconnected depending on how they move to achieve their global task (which does not include the connectivity maintenance). To retain connectivity, a number of Relay Agents (RAs), whose motion is governed by a command center (CC), are sent to the field to act as “communication bridges” enforcing the global connectivity of the network containing both the PAs and the RAs. Graph-oriented concepts and analysis tools, particularly the minimal spanning tree (MST) notion, are adopted in the present work to analyze the connectivity properties of the network and to establish in real time how many additional RAs are required and how they should move in order to prevent the connectivity loss. Artificial potential fields and finite-time control techniques are utilized to drive the relay agents to their waypoints while avoiding the collisions. Numerical examples confirm the efficacy of the proposed multi-layer control strategy.

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1. INTRODUCTION

Mobile Ad-hoc communication mesh NETWORKS (MANETs) that consist of multiple agents and perform cooperative tasks have many military and civilian applications (Bordetsky et al. (2010)), e.g. coping with crisis situations that arise due to natural or man-made disasters (Kanchanasut et al. (2007)). Reconnaissance, surveillance, and sensing through multi-robot networks have been the subject of much research (see, e.g., McLain et al. (2003); Olfati-Saber et al. (2007); Ren et al. (2007)). Within a related framework, recent results on finite-time consensus-based distributed coordination of uncertain multi-agent systems are also worth to remark (see Franceschelli et al. (2016, 2015)).

In typical sensing scenarios, for instance, a group of agents investigate a phenomenon of interest, with individual agents performing a primary data-gathering task while also meeting other requirements for network coordination. In such networks, each agent gathers its data and ensures network coordination by adapting to meet the system's goal. The research has based heavily on ideas from control, sensor networks, optimization, and graph theory (Jadbabaie et al. (2003); Mesbahi et al. (2010)), where information exchange and cooperation are key elements.

Loss of communication capability (i.e., loss of connectivity) in the mobile communication mesh networks could

result in loss of functionality of the entire application. Predicting and preventing loss of connectivity in the MANETs is a challenging task, which is usually performed using some form of traditional graph theoretic methods (Zavlanos et al. (2011)). Research in the robotics field on MANETs has also provided solutions to building and maintaining a communications bridge of mobile robotic routers (Tian et al. (2005)) to connect a mobile agent to a static base station.

In the majority of the existing approaches (see e.g. Zavlanos et al. (2011) and the references therein) all PAs can move to achieve the task of connectivity maintenance. Here, the motion of the PAs is not at CC disposal, and in order to retain connectivity CC is only in a position of sending the appropriate number of RAs to the field of operation. In Edwards et al. (2013), inspired by Zavlanos et al. (2011); Simonetto et al. (2011), all available RAs are in play and their way-points were computed through the solution of an optimization problem attempting to maximize the Fiedler value of a suitable “predicted” graph, that was called “phantom” graph. This approach brings, however, some drawbacks. The iterative solver could be unable to rapidly find a viable solution if the initial solution is not properly chosen. Additionally, the objective function is not available in analytic form, and thus its gradient has to be calculated numerically, which brings additional errors.

Recent research (see e.g. Misra et al. (2008); Holleran et al. (2010); Shtessel et al. (2012)) has recognized that an agent/node's primary task (for instance, reconnaissance) may potentially conflict with the MANET connectivity requirement. For the agent/node to perform its primary task successfully, it may have to move in such a way as to violate a movement constraint that keeps the MANET connected. In the other words, the primary agents/nodes of MANETs may not cooperate on retaining the MANET connectivity. At any instant of time, this situation can be interpreted and analyzed in terms of a graph, in which the primary mobile agents (PAs) are the nodes and the capability to communicate with other agents constitutes the edges of the graph.

This paper is dedicated to addressing the task of retaining the connectivity in such "conflicting" MANETs. To address this challenge, in this work it is proposed a multi-layered control architecture addressing the following tasks:

1. Predict loss of connectivity using concepts of "phantom graph" and minimal spanning tree. The graphs that are based on predicted positions of PAs are referred to as "phantom graphs" as they represent predicted future scenarios rather than actual ones. Specifically, in order to build the phantom graph, finite-time converging sliding-mode observers are used to estimate the velocities of PAs, then direct integration of kinematic equations of PAs is performed to predict the future trajectory of the PAs.
2. Identify isolated node(s) on the phantom graph. Specifically, the algorithm for identification of isolated nodes is obtained using the concept of the minimum spanning tree (Zavlanos et al. (2011)).
3. Compute and drop waypoints (that yield a connected "phantom" graph), where the additional nodes/relay agents (RAs) should be placed by certain time on the prescribed locations in order to retain the connectivity.
4. Compute feasible paths for the agents to follow. The design algorithm for the paths that connect the RAs with the waypoints while providing the collision avoidance with the PAs is proposed. Specifically artificial potential field and finite-time convergent control are the key ingredients of this item.

Addressing these tasks allows retaining the network connectivity via implementing self-forming and self-healing structure of the network.

The paper has the following structure. Section II deals with preliminary statements and definitions. Section III states the problem under investigation and the underlying assumptions. Section IV illustrates the general structure of the two-level proposed architecture, whereas the Sections V and VI explain in detail the upper and lower levels. Section VII formalizes the main result of the present paper, Section VIII gives some comments and Section IX presents numerical simulation results corroborating the theoretical properties.

2. PRELIMINARIES

2.1 Euclidean graphs

To model the connectivity properties of the mobile network, a graph-theoretic approach is taken. Denote as $q_i(t) \in \mathbb{R}^2$ the position vectors of the RAs, with $i \in V$ where $V = \{1, 2, \dots, N\}$ denotes the set of nodes indexed by the set of mobile agents. (i, j) denote a communication link between the i -th and j -th RAs, whose position vectors are $q_i(t), q_j(t) \in \mathbb{R}^2$. With every communication link, we associate a weight function

$$w : \mathbb{R}^2 \times \mathbb{R}^2 \rightarrow \{0, 1\}$$

such that

$$w_{ij}(t) = w(q_i(t), q_j(t)) = \begin{cases} 1 & \text{if } d(q_i(t), q_j(t)) \leq \beta \\ 0 & \text{otherwise} \end{cases}, \quad (1)$$

where

$$d(q_i(t), q_j(t)) = \|q_i(t) - q_j(t)\|_2 \quad (2)$$

is the euclidean distance between the i -th and j -th RAs and $\beta > 0$ is the *visibility range*.

A weighted time-varying Euclidean Graph (EG) $\mathcal{G}(t) = (V, W(i, j, t))$ is defined (see Zavlanos et al. (2011)) where $W : V \times V \times \mathbb{R}^+ \rightarrow \{0, 1\}$ denotes the set of edge weights, such that

$$W(i, j, t) = w_{ij}(t) \quad (3)$$

for $i, j \in V$ and $w_{ij}(t)$ as in (1)-(2). So defined, the graph $\mathcal{G}(t)$ turns out to have symmetric weights.

Definition 2.1. The EG $\mathcal{G}(t) = (V, W(i, j, t))$ is said to be *connected* if there exists a path between any pair of nodes having positive edge weights (1).

Graph connectivity can be captured using the Laplacian matrix $\mathcal{L}(t) \in \mathbb{R}^{n_p \times n_p}$ of the graph $\mathcal{G}(t)$, which is defined by

$$[\mathcal{L}(t)]_{ij} = \begin{cases} -w_{ij}(t) & \text{if } i \neq j \\ \sum_{s \in V/i} w_{is}(t) & \text{if } i = j \end{cases} \quad (4)$$

where n_p is the number of PAs. The Laplacian matrix of a network $\mathcal{G}(t)$ with symmetric weights is always a symmetric positive-semidefinite matrix with spectral properties closely related to network connectivity, as it can be seen from the following theorem (see Godsil et al. (2001))

Theorem 2.2. Let

$$0 = \lambda_1(\mathcal{L}(t)) \leq \lambda_2(\mathcal{L}(t)) \leq \dots \leq \lambda_{n_p}(\mathcal{L}(t))$$

be the ordered eigenvalues of the Laplacian matrix $\mathcal{L}(t)$. $\lambda_2(\mathcal{L}(t)) > 0$ if and only if $\mathcal{G}(t)$ is connected at time t .

2.2 Kinematics of primary and relay agents

Motion of the PAs and RAs is considered in the two-dimensional x - y plane. Let

$$p_i(t) = [p_{ix}(t), p_{iy}(t)]^T \quad i = 1, 2, \dots, n_p$$

and

$$r_j(t) = [r_{jx}(t), r_{jy}(t)]^T \quad j = 1, 2, \dots, n_r$$

denote the position of the i -th PA and j -th RA, respectively. A kinematic representation is given for the moving PAs and RAs. The motion of the i -th PA is modeled by

$$\dot{p}_i(t) = [v_{ix}^p(t), v_{iy}^p(t)]^T \quad (5)$$

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