Type of the Paper (Article, Review, Communication, *etc.)*

Self-Healing Connectivity for MANETs operating in Dynamical Environments

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Abstract: Field operations carried out by mobile users in inhospitable contexts, such as disaster relief or battlefield, require communication as effective and efficient as possible. A highly available Mobile Ad-hoc Network (MANET) could be a feasible communication platform for those contexts, provided high connectivity is achievable. In this article, a proactive distributed mechanism, referred to as a self-healing mechanism, to provide high connectivity for MANETs operating in inhospitable contexts is presented. This mechanism is based on enabling mobile users with short-range wireless communication and the introduction of additional unmanned vehicles acting as communication bridges, which proactively aim to detect and avoid network disconnections. Simulation results show that the proactive distributed self-healing mechanism proposed in this article allows MANETs to exhibit high connectivity under high values of network link failure probability. An analytical convergence model demonstrates, consistently with simulation results, that the system exhibits phase transition and becomes unreliable for link probability failure greater than 70%. Small-scale prototypes of the mechanism deployed on ground unmanned vehicles highlights issues such as location services, terrain constraints, and power. Conclusion for this work is that the self-healing connectivity proposed in this article is a feasible mechanism, provided the introduced mobile additional entities are able to quickly displace to areas requested and link probability failure is kept below 70%.

Keywords: MANET; self-healing; connectivity; communication

1. Introduction

Team operations conducted in highly dynamical and inhospitable contexts, such as disaster relief, need to be as efficient and effective as possible to mitigate as much as possible social and economic impact of such extreme events. In this context, a reliable team communication platform is a must [3]. Nevertheless, much of current communication platforms utilized in contexts such as disaster relief and battlefield are characterized by the use of voice channels [1, 2], which suffers from information overload and lacks the possibility of enabling a collective memory during operations, among other problems. A potential means to build such a communication platform is by using Mobile Ad Hoc Networks (MANET).

This article introduces a mechanism to avoid connectivity problems between mobile users operating in inhospitable environments, where each mobile user wears or carry on a short-range wireless enabled communication device. The mechanism is based on the introduction of autonomous unmanned mobile devices, here referred to as Mobile Communication Bridges (MCB), which perform simple tasks as antennas or signal repeaters that proactively and dynamically aim to maintain high connectivity in a MANET involving mobile users. Each MCB is enabled with the same technology that mobile users use; i.e., short-range wireless communication, battery, processing power. Hence, from a modeling perspective, the only distinction between the mobile users and the MCBs is their movement patterns. The movement of the MCBs is triggered by connectivity problems generated by the mobile users movement. For the design of a proactive movement behavior of the MCBs, in order to maintain connectivity in a MANET, one needs to evaluate fault tolerance, performance, and scalability, between centralized and distributed configurations in communities of unmanned vehicles [4]. This research effort made a decision in favor of a distributed approach, because in general fault tolerance and scalability are more tractable under a distributed approach than under a centralized approach [5]. Specifically, as the key issue to deal with in this research is fault tolerance, using a centralized approach which centralizes the coordination of the MCBs on one or a few nodes of the system could make the whole system more vulnerable, especially under deliberate attack or nonrandom failures of nodes and/or communication links [6].

Preliminary work on simulating the performance of the self-healing mechanism described in this article may be found in [35], which presents as key findings that the performance of the self-healing mechanism is resilient up to moderately high values of link failure probability and that this performance experiences a phase transition for higher values of such probability. This article presents new work, based on mathematical analysis and system development/prototyping, to check and better understand the results form preliminary work and the feasibility of the self-healing mechanism in real world contexts.

The remainder of this article is organized as follows: Section 2 introduces a review of the related work; Section 3 presents the self-healing mechanism; Section 4 shows a simulation model developed to evaluate the general performance of the self-healing mechanism; Section 5 presents a analytical model developed to better understand/confirm the dynamical convergence nature of the system as network link failure increases; Section 6 introduces a prototyping effort conducted to understand the impact of cell-phone location services and mechanical characteristics of small-scale robot platforms, and the impact of terrain on the proposed mechanism Finally, further work and conclusions are presented in Section 7.

2. Related Work

Research on coordination of mobile unmanned vehicles is a very active area, and several works have focused on analyzing the properties of wireless network connectivity [7]. Although usually obstacle avoidance, using adequate sensing and localization awareness mechanisms [9, 10], has attracted much attention from the research community [8], in recent years we have witnessed several research efforts gradually expanding the scope on sensing, communication, and coordination issues [4]; motion detection and data sharing approaches [11, 12]; and mobility prediction [13]. While many current research efforts still consider a person making decisions and controlling a community of unmanned vehicles [14], the idea of autonomous mobile actuators has been increasing in the mobile sensor community [15–17]. One of those efforts corresponds to the Self-healing Minefield (SHM) DARPA project [18], which has strong similarities and differences with the research presented in this article. Among the similarities are: the use of short-range wireless communication enabled mobile nodes and the existence of an autonomous distributed process in order to determine re-location of the nodes. On the other hand, the problem and the underlying approaches used between SHM and the research introduced in this article are different. First, SHM only considers a high probability of permanent failures of devices; i.e., the enemy destroys devices. In our case, permanent failures could be as high as in the SHM context, for the case of battlefield where an enemy aims at destroying nodes, or very low, as in the case of disaster relief contexts, where permanent failures may have not a significant impact [19]. Second, minefield healing is modeled as a statistical process [18], in opposition to the heuristic process carried out by the MCBs. Third, the objective of the research initiative presented in this article requires a proactive approach to dynamically avoid potential disconnections, while in SHM it is reactive; the healing process is activated once a networking breach has occurred; i.e., once a communication link has been destroyed. For the purpose of improving connectivity in a MANET operating in inhospitable context, a proactive pattern for the nodes involved in supporting communication seems more reasonable than a reactive one, through a distributed architecture [20]. Finally, in SHM the problem to solve is how to distribute the mines in a determined area so that the area covered by the network of mines becomes maximized, while for the research presented in this article the problem to solve is how the MCBs must proactively and collaboratively perform in order to maintain high level of connectivity within the MANET. Several other research efforts have addressed the area-maximizing problem [21, 22], but no specific research has been found regarding the specific problem stated in this article.

Another key issue related with distributed coordination in a community of autonomous mobile vehicles is message delivery. The research presented in this paper proposes the use of gossip-based multicast for MANETs comprised of a reduced number of nodes, e.g. 30 nodes, which is the case for teams responding to large-scale disasters [23], based on the results obtained by Haas et al. [24]. While Haas and colleagues focused on using gossip-based multicast for large MANETs, this work focused on determining a link failure probability threshold above which it can be guaranteed message delivery becomes highly reliable, but for small networks.

Research on autonomous dynamic networks is abundant and generally focused in data dissemination and communication issues, like UAVs collaborative communication systems [25]; urban surveillance operating on networks of vehicle sensors [26]; data spreading and availability [27]; or vehicle-to-vehicle information transmission [28], which is different to the connectivity problem approached in this article. Other related topics of interest, but not strongly tied to the work presented in this article, are: analyzing security mechanisms on protocols [29]; designing protocols to disseminate information about safety events in VANETs [30]; optimizing routing based on ratio of bandwidth used in data transmission to total bandwidth available and efficient algorithm bandwidth utilization to reduce redundancy [31, 32]; and modeling of mobility and networking on FANETs [33].

3. Self-healing Connectivity

The connectivity problem to address by this research is illustrated in Figure 1. In that figure P1, P2, P3, and P4 represent mobile users who communicate with each other using short-range wireless enabled devices, at a given time. Arrows represent the direction of movement for each mobile user. Thus, considering the direction of movement of each mobile user shown in Figure 1, P2 will eventually leave the communication range of P1, and vice-versa. The reader may find more details of the problem and a detailed description of the algorithm described below in [35].

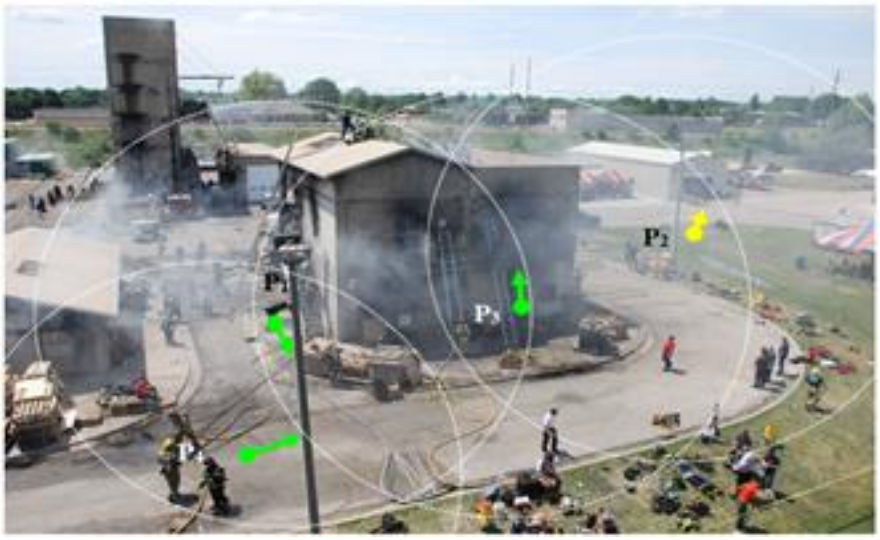


Figure 1. MANET= {P1, P2, P3, P4} will become fragmented, Set1= {P1, P3, P4} Set2={P2}.

To mitigate the occurrence of network fragmentations in a MANET, as depicted in Figure 1, the following three-phase mechanism has ben proposed [35]:

- **Potential disconnection detection phase**, this component is permanently running on every device. At every time step t, each node monitors its 1-hop neighbors; i.e., the neighbors inside its communication range. For each 1-hop neighbor that is located at a distance greater than a certain threshold, given as a parameter, the monitoring node keeps record of such distance. At the next time step, the monitoring node will determine the new distance for each previously monitored 1-hop neighbor. For each 1-hop neighbor, if the distance has increased, the monitoring node will try to find out if at least one of its other 1-hop neighbors is closer to the neighbor under observation. Only if the monitoring node determines that no other node is closer to the monitored node, it will consider that the node under observation is leaving its communication range and it will propagate a "potential disconnection" message through the network querying for an alternative route to the monitored node (see Algorithm 1, below).
- **Correction phase**, both mobile users and MCBs implement this phase. Once a node detected a potential disconnection, it will propagate a message through the network, using gossip-based multicast. Any MCB receiving that message will wait a given period of time for the counterpart message; i.e., the message sent by the other node involved in the potential disconnection. If the counterpart message is received by the MCB, it will ignore the situation, but, if the counterpart message is not received by the MCB, it assumes a disconnection is in progress. Thus, the MCB will move toward the potential disconnection area (the point at the middle of the line between the nodes involved in the potential disconnection). When the MCB sets itself for a connectivity task, it sends a multicast message, which includes its estimation of distance to the disconnection area, and starts moving (see Algorithm 2, below).
- **Maintenance phase**, this phase of the algorithm is applicable only to MCBs. Once the MCB is placed at the potential disconnection area, it tries to detect the presence of the requesting nodes. If the MCB does not find the requesting nodes after a given period of time, it will set itself back to Idle state. If the MCB detects the requesting nodes, it sets its state to supporting mode, adjusting its position dynamically based on the movement of the supported nodes. The MCB will remain in Supporting mode, until either the supported nodes are again in communication range; i.e., there is a route between the nodes which does not include the MCB supporting them, or the supported nodes are apart and the disconnection is imminent, making the MCB useless. In such case, the MCB will behave as a mobile user under similar situation; i.e., it will execute the potential disconnection phase (see Algorithm 3, below).

Algorithm 1: start-disconnection-detection // executed by any type of node in the system

```
while (1)
    if (clock() – time_last_check) > Δt
        for each 1-hop_neighbor[i]
            if (1-hop_neighbor[i].distance > threshold) &&
               (1-hop_neighbor[i].previousdistance < 1-hop_neighbor[i].distance)
               ask_others_1_hop_neighbor_if_closer_to(1-hop_neighbor[i])
               if no_other_1_hop_neighbor_closer_to(1-hop_neighbor[i])
                   gossip_search_alternative_path_to(1-hop_neighbor[i])
               end-if
            end-if
        end-for
        last_check = clock()
    end-if
end-while
```

Algorithm 2: Start-correction // MCB is on ON or ON_MOVING modes

```
while(1)
    if (receive_ alternative_path_messages(P1,P2))
      if (wait_deltaTime_for_ alternative_path_messages(P2,P1)==true)
```

```
            my_distance_to_target =calculate_distance_to_target()
              if received_gossip_MCB_moving(MCBiD,between(P2,P1))
                if (my_distance_to_target < received_distance_to_target)
                   MCB.mode = On_Moving
                   move_to_location(between(P1,P2))
                   gossip_MCB_moving(myMCBiD,between(P1,P2))
                   exit-while
                end-if
              else
              MCB.mode = On_Moving
              move_to_location(between(P1,P2))
              gossip_MCB_moving(myMCBiD,between(P1P2))
              exit-while
              end-if
      end-if
      else
      MCB.Mode=Off
    end-if
end-while
```

Algorithm 3: Start-maintenance

```
while (MCB.Mode == On_Supporting)
   new_position=between(determine_location_node(P1),
                 determine_location_node(P2))
   if (new_position == NULL)
      MCB.mode=Off
   else
      move_to_location(new_position)
   end-if
   if ((is_there_alternative_route(P1,P2)==TRUE) ||
     (is_there_alternative_route(P2,P1)==TRUE))
       MCB.Mode=Off
      exit_while
   end-if
   disconnection_detection()
end-while
```

This three-phase algorithm relies on two principles:

Principle 1: An MCB never loses members (mobile nodes) in Supporting Communication mode. While a node is in support mode it will not respond to messages from other MCBs that correspond to other potential disconnects. If communication with any of the supported nodes is affected by a potential disconnection, another MCB will be required for the correction and maintenance phase.

Principle 2: MCB never rejects a mission (potential disconnection call), unless other MCB is closer to such mission. Once an MCB has detected a possible disconnect, and determines that its distance to the disconnect area is closer than other MCBs, it will immediately be directed to the moving state area. If it is in motion and detects that other MCBs are closer to the area of possible disconnection, it will abort the mission and establish its status as Idle.

This three-phase algorithm and the principles rely on two assumptions. One of them is that the MCB set consists of homogeneous devices in terms of mobility and communication. With the ability to move at similar speeds. On the other hand, an obstacle free environment is assumed.

In this way the time of an MCB to reach the area of possible disconnection only depends on the distance to the destination. In a realistic scenario, where the routes can be blocked by physical objects, the second principle is still applicable for the evaluation of the abandonment of the missions with the difference that the minimum time to reach a destination must be used instead of the minimum distance to such an area.

4. Simulation

As mentioned in the introduction, preliminary work on simulating the performance of the self-healing mechanism described in this article may be found in [35]. That article describes the details of the simulation model built to simulate the performance of the self-healing mechanism and the results obtained from such effort. In the following paragraphs only the main aspects from the model and results described in [35] are presented for the convenience of the reader.

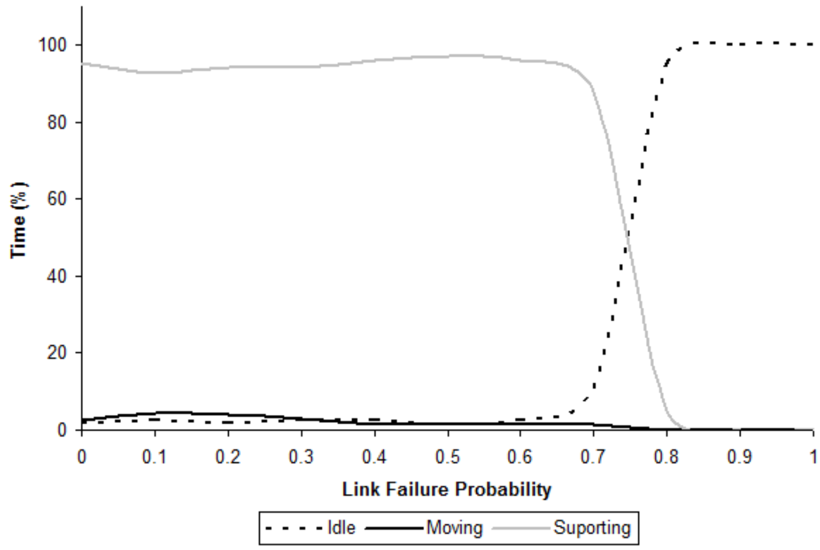


Figure 2. Simulation highlights that the self-healing mechanism works well for conditions that define a link failure probability lower than 0.7; most of UCBs are in supporting mode, while only a few are in Idle or moving (toward required location to provide connectivity) mode.

A discrete event simulation model was built on a 2D operations area, a square of side 400 m, with the first responders moving randomly and MCBs moving depending on the movement of the first responders. Each node is modeled with GPS functionality, and MCBs are always in one of three modes: (1) Idle, (2) Moving toward a required communication area, and (3) Supporting Communication. The communication is based on gossip-multicast and there are no obstacles in the 2D space.

One of the key results obtained in [35] is the relationship between link failure probability (LFP) and the reliability of the self-healing mechanism observed in Figure 2. For a LFP lower than 0.7 the MCBs are mainly in Supporting mode, while for a LFP greater than 0.8 the MCBs are mainly in Idle mode. For a value of LFP between 0.7 and 0.8 the system suddenly experiences a phase transition. Put in other words, the self-healing mechanism becomes useless for values of LFP greater than approximately 0.75. This perspective of system dynamics is analyzed in detail from an analytic focus in the next section.

5. Dynamics of the Self-Healing Mechanism

The results shown in the previous section correspond to the analysis of the system from a micro level point of view. In this section, it is our intention to bring major clarity on the dynamics of the system, particularly to better understand the phase transition shown in Figure 2. Thus, the following analytical model is developed:

Let S_n be the number of MCBs in Supporting Communication mode, I_n the number of MCBs in Idle mode, and M_n the number of MCBs in Moving mode at time step n. As the total number of MCBs, N (in this case N represents a large number of nodes), is considered constant, we have:

$S_n+I_n+M_n = N$ if we consider $s_n=S_n/N$, $i_n=I_n/N$, and $m_n=M_n/N$, then: $s_n+i_n+m_n=1$

The diagram shown in Figure 3, describes the states each MCB may be at a given time. For simplicity, this research is focused on investigating the applicability of the healing process; i.e., centered on the dynamics of Supporting Communication mode, it is considered $x_n=i_n+m_n$. Accordingly, using the following coupled maps the dynamics of this system may be approached:

$$x_{n+1} = x_n + p_{sx}s_n - p_{xs}x_n \quad (1)$$

$$s_{n+1} = s_n + p_{xs}x_n - p_{sx}s_n$$

The system in (1) has one attractor at

$$\left(\frac{p_{sx}}{p_{sx}+p_{xs}}, \frac{p_{xs}}{p_{sx}+p_{xs}}\right) \quad (2)$$

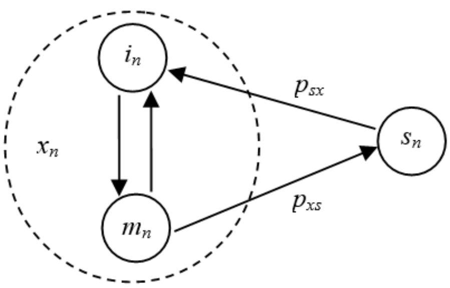


Figure 3. States diagram representing the proportion of MCBs in each state; i.e., i = Idle; m = Moving; and s = Supporting. States i and m comprise the state x, and p_{ij} represents the transition probability, per round, from state i to state j.

To evaluate the behavior of the attractor of the system shown in (1), it is required to model the transition probabilities or rates between the states x_n and s_n. The probability for a MCB to transit from Supporting Communication to Idle is given by:

p_{sx} = *Prob((nodes supported by the MCB become able to communicate without the support of the MCB) OR (MCB does not receive answer from supported nodes to request messages generated by the MCB))*

The first component of p_{sx} represents the probability the nodes supported by the MCB will be able to communicate each other without the need of the MCB; i.e., the probability they will be in communication range given their movement pattern, $\gamma \in [0,1]$, times the probability such situation is monitored by the MCB. The second component of p_{sx}, represents the situation when both messages are not received. Hence, the following expression is obtained for p_{sx}:

$$p_{sx} = LFP^2 + \gamma(1 - LFP)^2 \quad (3)$$

On the other hand, the probability for a MCB to transit from the combined state Idle & Moving to Supporting Communication can be modeled as:

p_{xs} = Prob(MCB in Idle state receives potential disconnection messages & MCB is "chosen" to support potential disconnection)

The first component of p_{xs} is modeled as proportional to the probability a MCB receives a potential disconnection message. Here, LFP corresponds to the link failure rate per time step. The second component of pxs, is modeled by introducing parameter $\lambda \in [0,1]$, which represents the ratio between the number of disconnections perceived by MCBs and the number of MCBs available to respond to disconnection calls at a given time. Hence, the following expression is obtained for p_{xs}:

$$p_{sx} = \lambda(1 - LFP) \tag{4}$$

Combining equations (3) and (4) into (2), the plot shown in Figure 4 is obtained. This plot shows how the dynamics of the system is affected by the parameters LFP, λ, and γ. This plot confirms the dynamics shown by the graph in Figure 3.

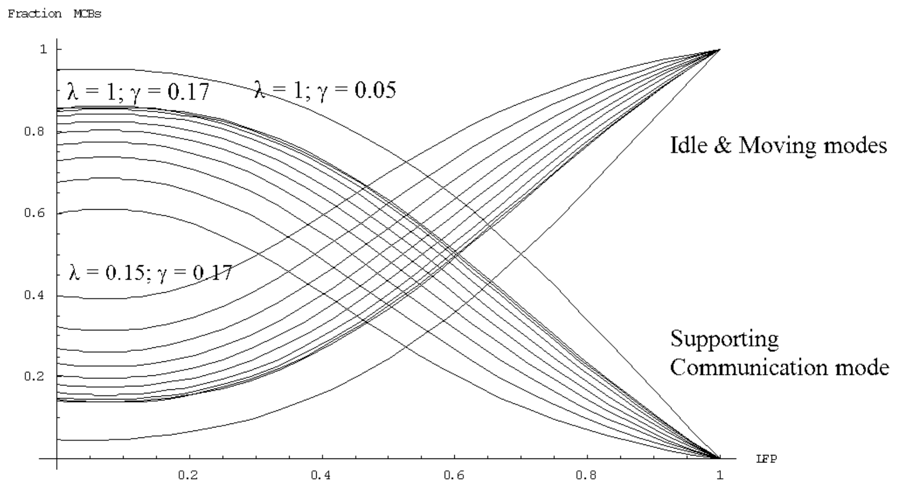


Figure 4. Impact of Link Failure Probability (LFP) on the attractors of the dynamics of the self-healing mechanism; a different pair of curves is obtained for different values of λ (the rate between the number of disconnections perceived by MCBs and the number of MCBs available to respond to disconnection calls). The lower the value of λ, the lower the LFP threshold on which the phase transition would occur. The LFP threshold for a phase transition to occur corresponds to the x value at the intersection of the pair of curves (decreasing curve represents Supporting mode, increasing curve represents Idle & Moving modes) for each λ.

Although the main purpose of the analytical model developed in this section is to obtain a qualitative view of the dynamics of the system, in contrast to the quantitative and detailed view obtained through simulations, important outcomes are possible to be elaborated by analyzing both Figure 2 and Figure 4. First, not surprisingly, for a MANET comprised of mobiles users which has a permanent demand for MCBs to provide connectivity, the self-healing mechanism will tend to collapse as the reliability of the communication decreases; i.e., a link probability failure greater than 0.7. Put in other way, the more reliable the message delivery used for the nodes of the MANET to communicate; i.e., mobile users as well as MCBs, the more efficient the utilization of MCBs. Also, the self-healing mechanism will require the MCBs spending more time in Supporting mode in settings where the probability of reencounter (communication range) between nodes communicated through MCBs; i.e., γ, is lower. Regarding vulnerability, for the self-healing mechanism to be less vulnerable to link failures, the proportion of MCBs in Idle (& Moving) state should be kept as close as possible to the demand for supporting disconnections; i.e., $\lambda \rightarrow 1$. Finally, a very interesting outcome is that the dynamics of the self-healing mechanism obtained through the analytical model, which considers a large number of MCBs, and consequently a very large number of mobile users, is similar to the dynamics obtained from simulation runs considering small scale MANETs.

6. System Prototypes

The prototyping effort involved small-scale unmanned ground vehicles (UGV); robot platform carrying a cell phone, operating under different outdoor conditions. The processing unit, GPS location service, electronic compass, and other sensors correspond to the ones available in an Android cell phone. This unit is connected to the vehicle-robot platform to effect the required movement. In terms of MANET components, the system has two elements: a) mobile user module; each node will broadcast its coordinates while it moves freely (Figure 5 (a)), and b) unmanned vehicle module; which permanently monitors service request calls and once it determines its role is needed to avoid or mitigate disconnections, assists it until it's not needed anymore, returning back to a pre-defined location. To establish and calculate the direction of movement, the unmanned vehicle module calculates the current angle with respect to the North, through its GPS service, and in parallel it calculates the same angle but with the coordinates of the midpoint between the mobile users to be supported. Comparing both angles and verifying them with the header information gathered from the magnetic compass, it is determined where should be the midpoint between the two nodes that are requiring connectivity support.

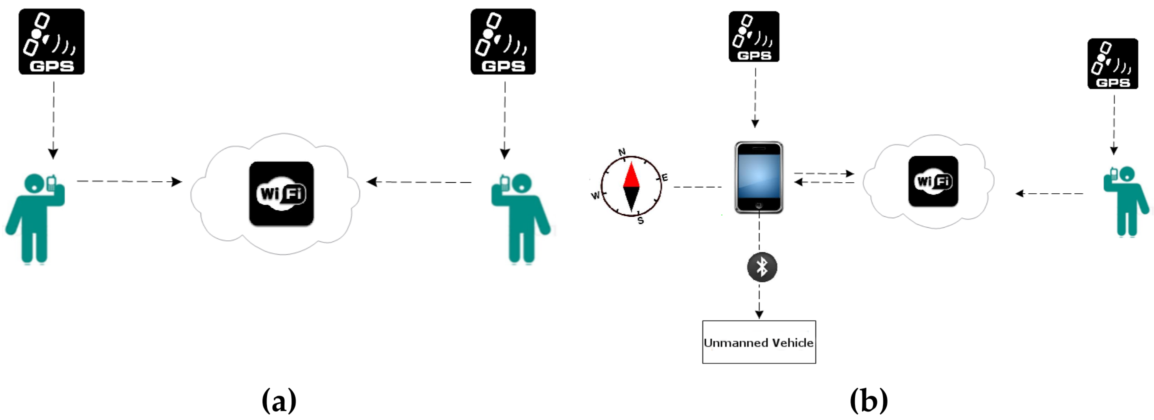


Figure 5: Software modules: a) mobile user module, and b) unmanned vehicle module.

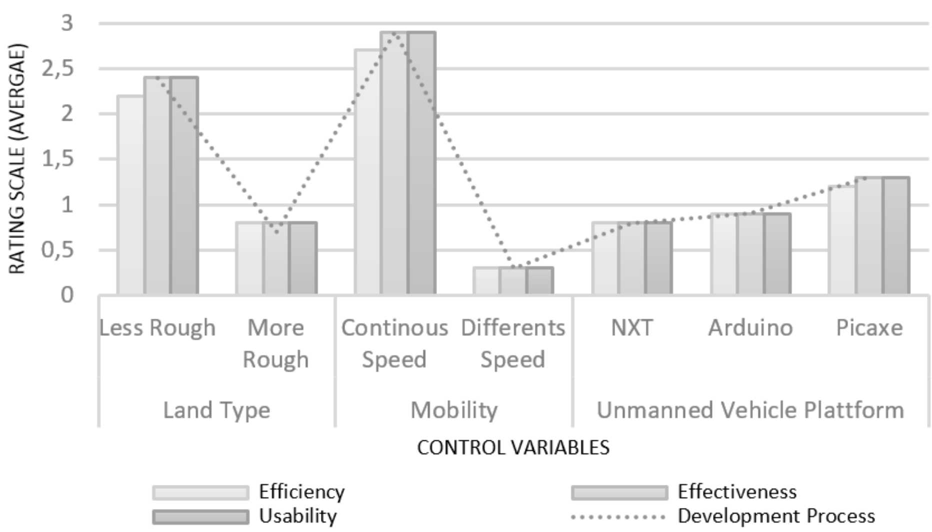
The prototype described in this section was evaluated on three aspects: control variables, dependent variables, and errors and failures parameters (Table 1). The control variables are terrain type, mobility, and robot platform. Terrain type ranges from Less Rough, corresponding to flat clean surfaces/tarmac, while More Rough corresponds to ground terrain with imperfections and / or with pebbles/rocks on the surface making more difficult the displacement of small-scale unmanned vehicles. Mobility is the movement pattern; continuous or varying speeds. The Robot Platform is the architecture and model of small-scale robots: Mindstorm NXT, DFRobotShop Rover V2 (Arduino), and a platform built with Picaxe components. All prototypes developed where tested in a setting involving two people and one UVG. The initial layout involved the two people with line of sight and located within WiFi communication range, about 20mts apart, and the UVG located at a pre-defined location, about 30mt orthogonal to an imaginary line between the two people. After this initial layout, the people started to walk in opposite location until the UVG started to move to the point in between the two people to provide connectivity. Finally, after the UVG located itself near the point between the two people, the people started to walk to each other again, checking the UVG moved back to its initial location.

Table 1. Prototype variables and metrics

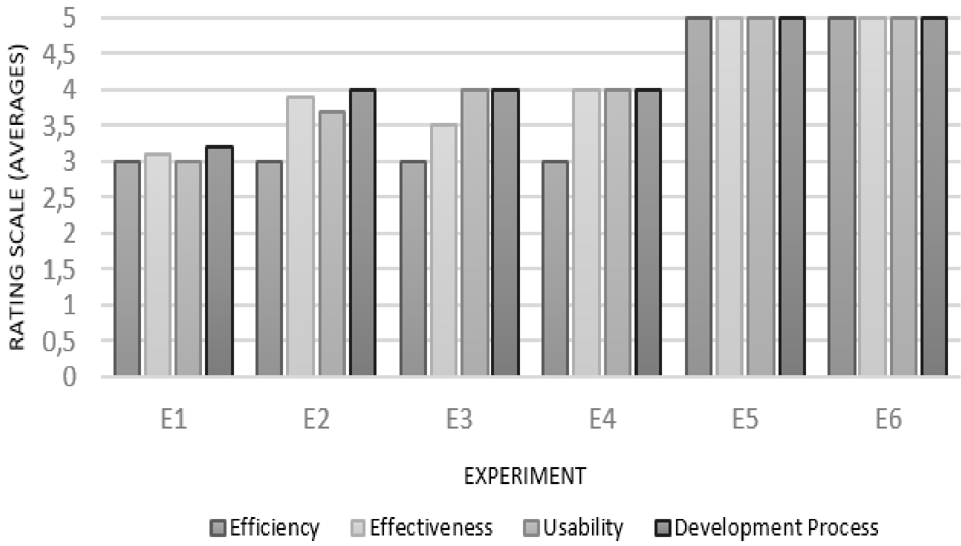
Type	Parameters

Control Variables						
Terrain type	Less Rough			More Rough		
Mobility	Continuous Speed			Different Speed		
Robot platform	Nxt		Arduino		Picaxe	
Dependent Variables						
Robot movement	Orientation		Activation	Movement	Deactivation	
Robot times	Orientation		Activation	Movement	Deactivation	
Algorithm behavior	Detections	Corrections	Midpoint Position	Maintenance	Return	Starting Position
General aspect Experiment	Efficiency	Effectiveness		Usability	Development Process	
Errors and Failures	% total failure perceptions	% total errors found		% total of bugs fixed		

The results obtained through prototype experimentation shed light qualitatively understanding the pertinence of the self-healing mechanism to maintain/improve connectivity in a MANET used for field operations. Figure 6 (a) presents a summary result for several experiments conducted {E_1, E_2, E_3, E_4, E_5, E_6} to determine correlations between control and dependent variables. From there it is evident that the better conditions to reduce the chance of having the MANET experiencing disconnections occurs when a) the UGVs move on a flat/clean surface, compared to movement occurring on less clean/flat surface where the movement was below average exhibiting longer times to reach expected destination; b) continuous movement of UGVs, rather than varying speed movement, showed better performance across all phases of algorithm; and c) the PICAXE robot platform, over the other two options NTX and Arduino. Figure 6 (b) presents evaluation of efficiency, effectiveness, usability, and easiness of development/maintenance associated with each round of experimentation. This plot remarks how every one of these factors improves significantly through the continuous improvement process used to develop the prototypes. Ultimately, all factors are satisfactorily achieved, highlighting that a continuous refinement of prototype development has a significant impact on the quality of the tool built to test the self-healing mechanism, and it’s important to differentiate this aspect from the three-phase self-healing mechanism itself, and potentially from the type of MCBs used to implement the system; ground unmanned vehicles or Aerial Unmanned Vehicles (AUV).



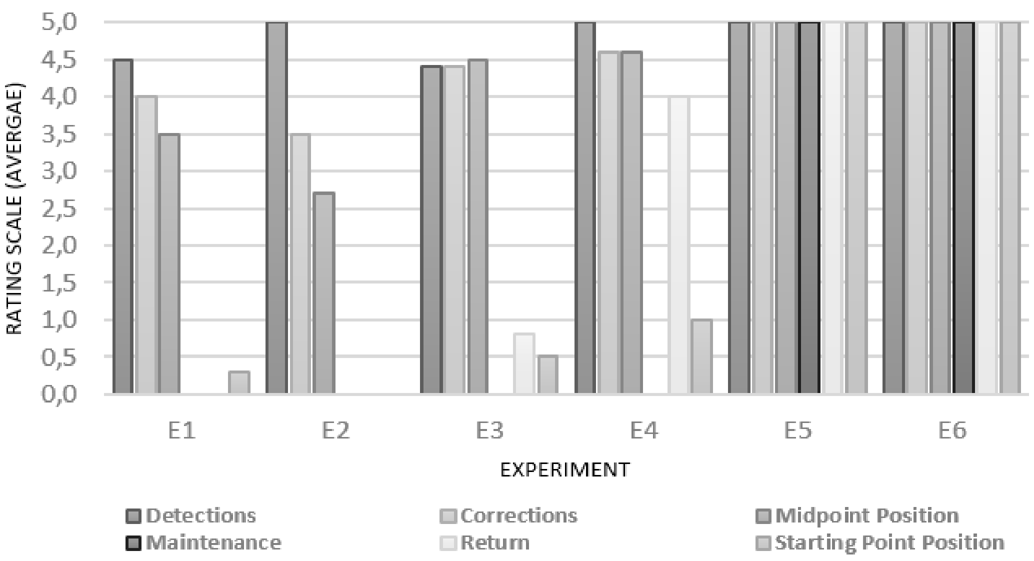
(a)



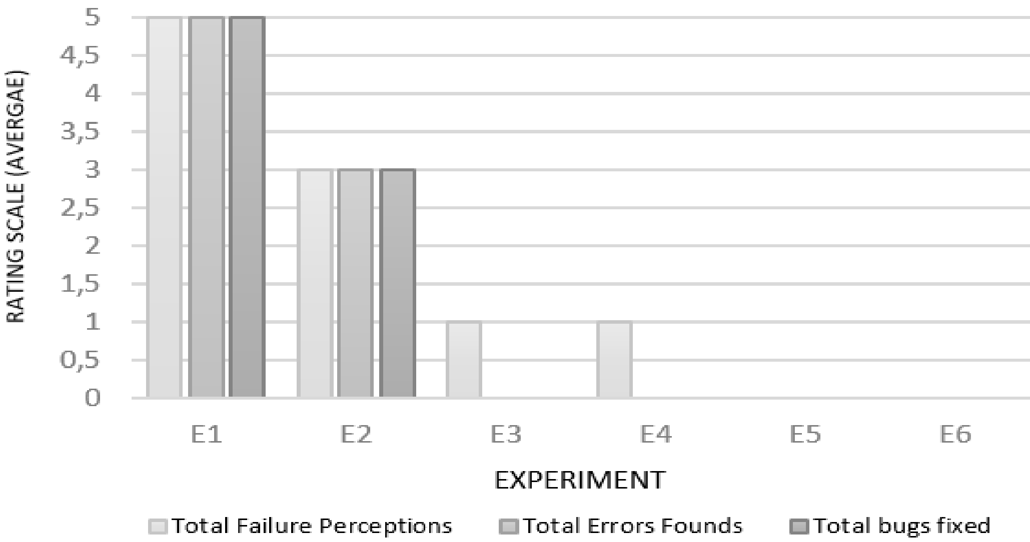
(b)

Figure 6. Impact of control variables and continuous refinement on prototype development and testing: (a) relevance of control variables on prototype performance; and b) evaluation of efficiency, effectiveness, usability, and development effort through experiments set. Y-axis: 0 – not observed, 1 – very bad, 2 – poor, 3 – fair, 4 – good, 5 – excellent.

Regarding the performance of the self-healing algorithm, in its three phases: potential disconnection, correction, and maintenance, as well as in placing the UVG at location to provide connectivity and bringing it back to initial location when its support was not needed anymore, it was clearly observed that the performance of the prototype improved with depuration of code and algorithms implementation during repetitions of the experimentation (see Figure 7). The need for the continuous improvement of the prototype is so evident when one starts to observe the impact of real world on the design of the algorithm. For example, the displacement of the UVG towards the "middle" point between the two people moving is very sensitive to the speed at which the people walks, the speed of the UVG itself, the quality of the electronic compass readings (in the cell phones), and the quality of the GPS readings, i.e., if for whatever reason the UVG has a mechanical issue with one wheel that makes it drift towards left or right it will continually struggle to correct its movement direction towards the middle point between the people walking in opposite directions, sometimes this displacement is just not working well. Mechanical symmetry of UVG and wheel movement quality had to be checked frequently to have the self-healing mechanism to operate as expected. Extra code had to be placed to take these sorts of little mechanical/sensors capability issues. A significant number of errors and/or anomalies in functionality of the prototype had to be treated and fixed before the prototype acted as expected. It is clear that reality imposes an empirical layer, not able to be detected in simulation runs.



(a)



(b)

Figure 7. Three-phase algorithm (disconnection, correction and maintenance) performance change during: (a) tuning, and (b) error reduction, while experimentation.

The fact that the terrain and mobility of the Mobile Communication Bridges is so crucial and relevant for the success of the self-healing connectivity mechanisms suggests that an option for the MCBs based on Unmanned Aerial Vehicles (UAV) maybe a better option to maintain and improve connectivity in a MANET comprised of mobile users operating in outdoor spaces.

7. Conclusions and Further Work

This article presents a completely distributed self-healing mechanism to improve the connectivity in MANETs under inhospitable environments, where an infrastructure communication is not reliable or does not exist. Specifically, the self-healing mechanism is based on deploying unmanned vehicles, enabled with short-range wireless communication technology, which perform a simple task; act proactively on demand of potential disconnections generated by the mobility of the mobile users. If the self-healing mechanism is applied, high connectivity could be guaranteed for a smaller team of mobile users operating in the same area. This conclusion can also be stated from a different perspective: for a given fixed number of mobile users who comprise a team, who comprise a MANET, the self-healing mechanism allows them to keep high connectivity in larger areas. In addition, from the perspective of the entire system, the use of the self-healing mechanism represents an energy saving option if it is compared to the option of deploying unmanned vehicles in permanent pseudo-random movement.

Link failure probability is a key factor for the system. Through simulations it is demonstrated that the self-healing mechanism, and consequently the connectivity of the MANET, is resilient up to moderately high values of link failure probability. Nevertheless, the system experiences a clear phase transition, it suddenly switches from active to inactive; i.e., unmanned vehicles set themselves to Idle mode, for higher values of link failure probability.

The dynamical system analysis developed confirms the simulation results and suggests that the self-healing mechanism operates normal for values of link failure probability below 70%. The analysis also suggests that this performance threshold would not only be experience by small or medium size networks, but also by large size networks.

Further work will be oriented to increase the performance, and consequently the scalability, of the designed self-healing mechanism, exploring the impact of different multicast strategies like tree-based multicast, e.g., [34], as well as to make the system even less vulnerable to link probability failures in more complex settings involving physical objects according to different inhospitable contexts. Analyses of different movement strategies for the MCBs are also part of future work.

From the system prototyping effort it may be asserted that: a) best performance is obtained when terrain is clean and flat; MCBs are continuously moving at a constant speed; and the quickest or more agile robot platform is used to carry the cell phone, and b) fact that the terrain and mobility of the Mobile Communication Bridges are so important for the success of the self-healing connectivity mechanisms suggests that an Unmanned Aerial Vehicles (UAV) option may be a better technology for the self-healing mechanism for MANETs used in emergency response or military contexts.

Finally, reality imposes an empirical layer, not able to be detected in simulation runs, which demanded a significant effort in algorithm, but mainly in mechanical soundness of UVGs, to be able to have the prototypes performing as expected. This work demonstrates the feasibility of the self-healing connectivity mechanism for MANETs operating in outdoor emergency or military contexts, provided that a suitable platform is chosen to play the role of the Mobile Communication Bridges.

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