Design of an Emergency MANET Based on Cellular Phone Technology

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Abstract

In cases of natural or man-made disasters there are often survivors and emergency forces need situational awareness information on how to optimally deploy their resources. Natural disasters such as fires, floods, or earthquakes can lead to the loss of electricity and internet connectivity and cellular towers might not be operating. One possible solution is to have a mobile ad-hoc network (MANET) based on cellular phone technology that can be activated during an emergency situation. In this investigation we use simulation techniques to optimize the design of an Emergency MANET in terms of communication protocols which maximize the probability of survival of disaster victims.

Keywords: mobile ad hoc networks, cellular phone, broadcast routing, wireless mesh networks

1.0 Introduction and Background

In cases of natural or man-made disasters there are often survivors and emergency forces that need information on how to optimally deploy their resources. Many people died after the tsunami off the coast of Honshu, Japan on March 11, 2011, because rescue workers were not able to locate people buried in the rubble. Natural disasters such as fires, floods, or earthquakes can lead to the loss of electricity and internet connectivity and cellular towers might not be operating. Something that has become a common occurrence in natural disasters is that people use social media to publish disaster related content. Google's response to the Japan Earthquake was to provide Google Person Finder, an application that allows people in Japan to provide information about people including their location. This application also allows people to search for a particular person.

Another possible approach is to have a mobile ad-hoc network (MANET) that can be activated during an emergency situation. A MANET is a collection of autonomous mobile users that communicate over bandwidth constrained wireless links where the nodes not in direct communication range use intermediate nodes to communicate with each other (NIST, 2013; IETF, 2009). Since the nodes are mobile, the network topology may change unpredictably over time. The network is decentralized, where all network activity including discovering the topology and delivering messages must be executed by the nodes themselves. Significant examples include establishing survivable and efficient communication for emergency/rescue operations (Jang et al., 2009), vehicular traffic information (Blum et al., 2004) and military networks (Burbank, 2006). In these cases, situational awareness, information availability and information integrity are critical. Information needs to be shared and therefore needs to be sent in the clear however at the same time the integrity of the information must be protected. For example, in an Emergency MANET, it is critically important for the information to get through to its destination without error as it contains the GPS location of potential victims and rescue teams must allocate their resources efficiently using situational awareness data.

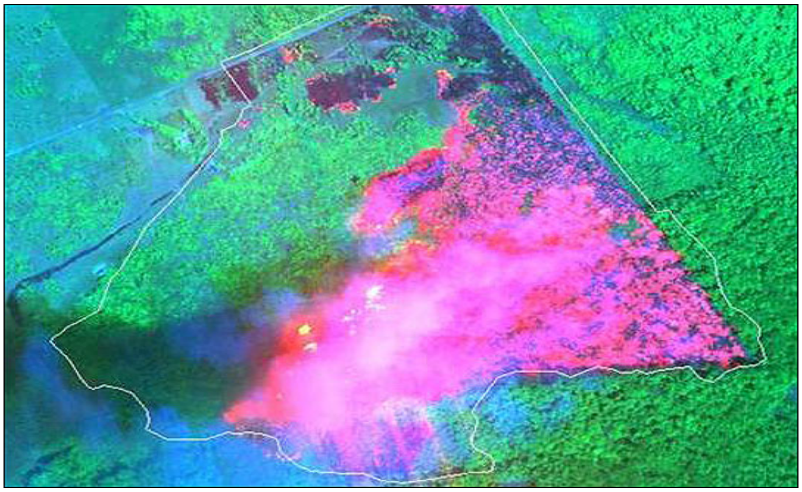

Figure 1: Thermal Image of San Diego Brush Fires (courtesy of NASA)

2.0 Emergency MANETs

The concept of emergency MANETs is still in its infancy (Jang et al., 2009; Navy, 2010). In cases of natural or manmade disasters there are often survivors and emergency forces need information about how to optimally deploy their resources. Natural disasters such as fires, floods, or earthquakes can lead to the loss of electricity and internet connectivity and cellular towers might not be operating. Rapid deployment of a communication network is needed and a mobile ad-hoc network could provide the required solution. There are several problems that need to be overcome to implement such a network. There are different brands of cellphones which may or may not be compatible with relay messages. A software application must be previously downloaded to participate in the emergency MANET. A centralized control center has to send an activation signal during the emergency. The network should also be agnostic of cellphone service provider. Information can be relayed from one rescue team member to another over a small handheld.

An application embedded in the cellular phone could be used to communicate GPS coordinates which then can be superimposed onto a map. For example, the hyperspectral image in Figure 1 which shows satellite thermal image of brush fire spreading rapidly by the Santa Ana winds near San Diego, California. This is an example of hyperspectral imaging which can collect, measure, and analyze reflected light in the form of a spectral fingerprint revealing information that is not visible to the naked eye. Currently, it might not be possible to get a real-time satellite image of a given natural disaster. However, one might fuse data from other sources such as drones or helicopters. Twitter, for example, captures geotag metadata that contain longitude and latitude coordinates in the tweets (Middleton et al., 2013). The use of a social media platform, with their mix of content that can be analyzed in real time as seen in Middleton et al. (2013) and the location data itself can capture the user's location data which could help with search and rescue. The value of such a capability was demonstrated by the San Diego State University Visualization Center (Viz, 2010), which assisted in emergency efforts during the 2010 Haiti earthquake.

Being able to gain mobile phone location data would allow first responders to be able to begin their relief efforts with more of a precision strike than an exploratory endeavor. Unfortunately there are several problems with this approach. For one thing it does not address the question of who is going to get this information and how this information will be shared with rescue workers. It appears unrealistic to assume the cellular service provider will provide this data in a timely manner. Having an application like Google Person Finder is a way for a person to share their whereabouts or for another person to bring awareness of a person's disappearance. But emergency response needs to be performed in a timeframe of hours and minutes, not days. Sometimes people are not in a position to personally send out a distress call. A more timely way to handle this type of emergency situation is for the mobile device to automatically send the distress message through a mobile ad-hoc wireless mesh network independent of the service provider.

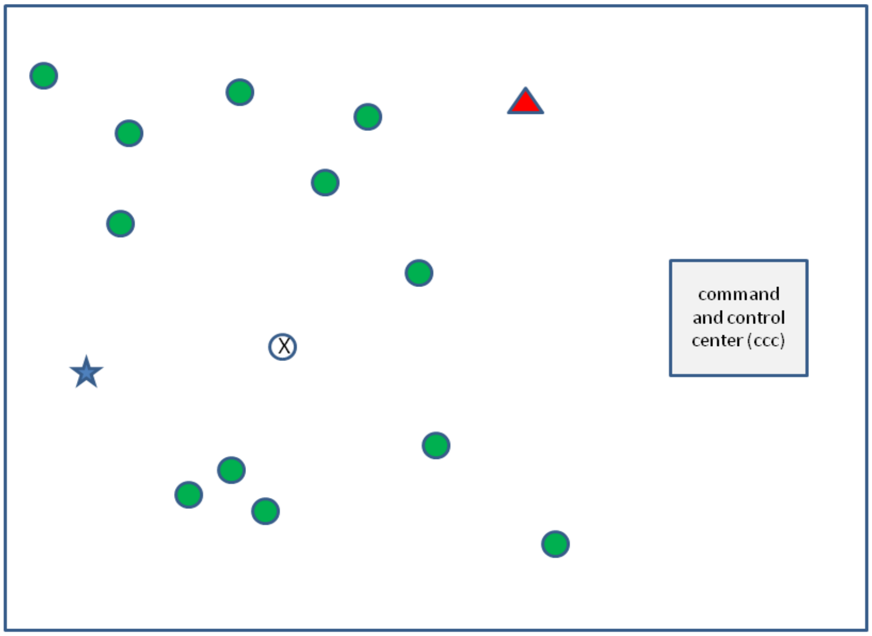

Figure 2: Identification of Nodes in an Emergency MANET

3.0 System Architecture and Operation

Consider an emergency MANET deployment scenario as illustrated in Figure 2 in a natural disaster area. In this example, the green circles represent stranded individuals, the blue star represents law enforcement and the red triangle represents firefighters. The white circle represents a high-powered transceiver that optionally can be deployed to improve communication when nodes are out of range or when obstacles inhibit communication (it can also optionally provide internet access). The Command and Control Center (CCC) may be far away at a fixed permanent location or located temporarily near the disaster. It too, is optional. The nodes of the network could be cellular phones or other mobile or handheld devices. It is assumed that the individual nodes are running an application which supports the sending of the GPS and other information such as text messages. The MANET is activated by an administrator and can only be activated during an emergency situation. It is assumed that all of the cell phones configured for the MANET application will be listening on some pre-designated port for an activation message. The nodes of the network form a Wi-Fi mesh based on broadcast routing. The mobile ad-hoc network must be ready to operate instantly at any time without the need to deploy any additional equipment. This could be done by embedding an application in every cell phone and using the cell phones themselves as hubs and routers. The cellphone application should adapt its communication protocols automatically based on the amount of battery power remaining.

The most important information that needs to be communicated to the command and control center is the GPS location of the individual nodes and the network should be optimized to this purpose. The location of the individual nodes can then be superimposed onto a map or hyperspectral satellite image (as shown in Figure 1). This superposition could be performed automatically at a central command and control center and used to direct appropriate rescue workers. Some members of the rescue team could be assigned to search social networking media to find relevant information and fuse that information with the information received from the Emergency MANET. This type of dynamically changing situational awareness information can be critical to saving life and property as the locations of rescue forces, stranded individuals, and fire intensity can change significantly in a short time period as rescue workers move towards their targets and stranded individuals move to avoid imminent danger.

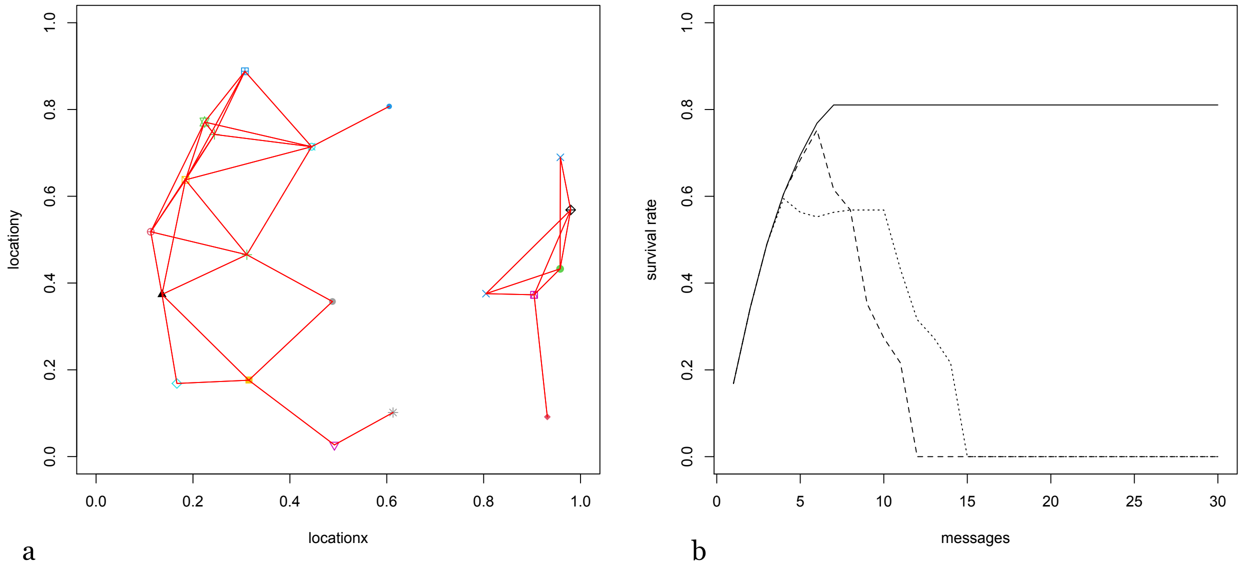

Figure 3: Emergency MANET simulation

4.0 Results of the Emergency MANET Simulation

Our initial simulation technique assumed a uniform distribution of mobile devices across a 2-dimensional space as shown in Figure 3(a). The transmit power of each device was adjusted so that the devices formed a relatively small number of subnets. If the power were set too high, there would be connectivity between all devices and only one subnetwork (the entire network). If set too low, then none of the devices would be able to communicate with each other. Using a trial and error approach we adjusted the transmit power to an intermediate value which resulted in a small number of subnets which varied each time we ran the simulation. For the example in Figure 3(a) the network partitioned itself into 2 subnetworks with about 80% of the devices in one subnet and 20% in the other. Using the (x, y) location coordinates for each device we created a matrix representing the probability of a message being sent by node i and received by node j. The Euclidean distance between each pair of nodes was used to calculate the probability using the inverse square law to reflect the isotropic propagation of transmitted electromagnetic energy from each device. We assumed a simple broadcast routing where any device receiving a message would include it in its next broadcast but not in any subsequent broadcasts unless it received it again.

Using Markov chain analysis, we were able to compute the probability of a message being broadcast by any node i being received by node j after n transmissions and the result is given in Figure 3(b) for 3 different battery drain profiles. The solid line represents a fully charged battery and full transmit power for each message. The dashed line shows a partially-charged device transmitting at maximum power for each message until the battery drain starts impacting the range of transmission after 6 or 7 messages. The dotted line shows a device that starts out sending messages at full power but lowers the transmit power after 4 or 5 messages to conserve energy. The survival rate indicated on the y axis represents the fraction of mobile devices in the whole network that a device has managed to get at least one message to after transmitting "x" number of messages. For this example, the devices are located in the subnet containing 80% of the devices in the network. After sending about 10 messages at full power a device will have reached every other device in the subnetwork but only about 80% of the devices in the whole MANET.

The result of the simulation gave significant insight into how to design the communication protocol for each mobile device based on its remaining battery power. It also became clear that a minor modification of the standard broadcast routing would increase the probability that a message would successfully reach its destination. Instead of retransmitting received messages as in traditional broadcast routing, each mobile device should aggregate all previous messages into each subsequent message. Using this method, mobile devices that had more battery reserve would act as proxies for other devices after they ran out of power.

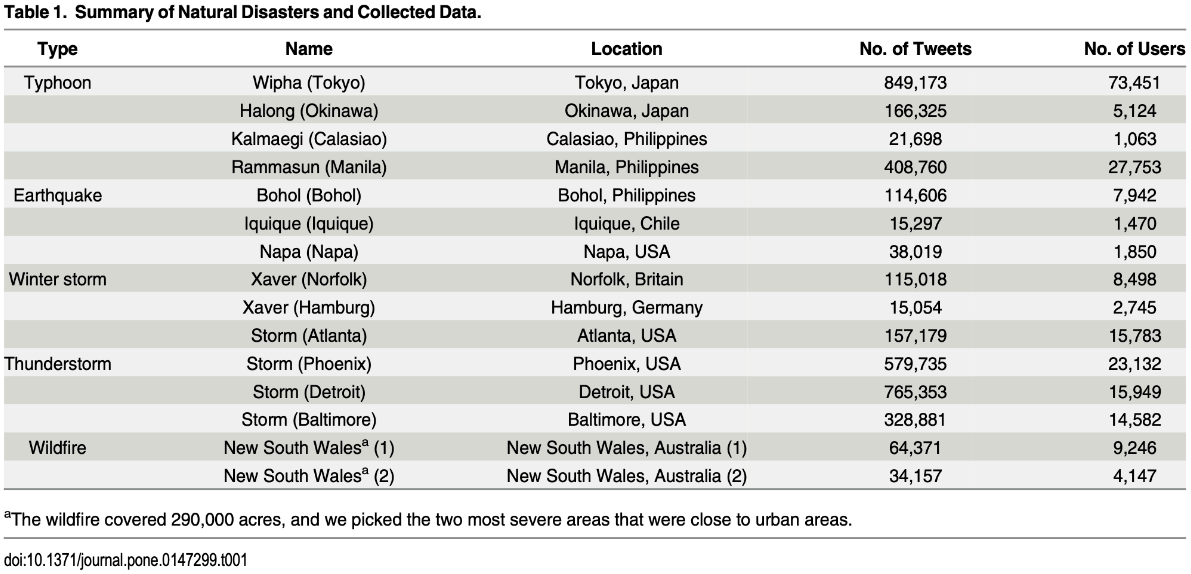

Table 1. Summary of Natural Disasters and Collected Data.

Type	Name	Location	No. of Tweets	No. of Users
Typhoon	Wipha (Tokyo)	Tokyo, Japan	849,173	73,451
	Halong (Okinawa)	Okinawa, Japan	166,325	5,124
	Kalmaegi (Calasiao)	Calasiao, Philippines	21,698	1,063
	Rammasun (Manila)	Manila, Philippines	408,760	27,753
Earthquake	Bohol (Bohol)	Bohol, Philippines	114,606	7,942
	Iquique (Iquique)	Iquique, Chile	15,297	1,470
	Napa (Napa)	Napa, USA	38,019	1,850
Winter storm	Xaver (Norfolk)	Norfolk, Britain	115,018	8,498
	Xaver (Hamburg)	Hamburg, Germany	15,054	2,745
	Storm (Atlanta)	Atlanta, USA	157,179	15,783
Thunderstorm	Storm (Phoenix)	Phoenix, USA	579,735	23,132
	Storm (Detroit)	Detroit, USA	765,353	15,949
	Storm (Baltimore)	Baltimore, USA	328,881	14,582
Wildfire	New South Wales[a] (1)	New South Wales, Australia (1)	64,371	9,246
	New South Wales[a] (2)	New South Wales, Australia (2)	34,157	4,147

[a] The wildfire covered 290,000 acres, and we picked the two most severe areas that were close to urban areas.

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5.0 Application to Previous Natural or Man-Made Disaster Events

Perhaps the most famous Emergency MANET in history involves the ship RMS Titanic (Wikipedia, Titanic). On April 14, 1912 the Titanic hit an iceberg at 11:40 pm when 375 miles south of Newfoundland Figure 6(a). At 2:20 am, the ship broke apart and foundered, with well over one thousand people still aboard. Distress signals were sent by wireless, rockets, and lamp, but none of the ships that responded were near enough to reach Titanic before she sank. The transmitter was one of the most powerful in the world and guaranteed to broadcast over a radius of 350 miles. A radio operator on board the SS Birma, for instance, estimated that it would be 6 am before the liner could arrive at the scene. Meanwhile, the SS Californian, which was the last to have been in contact before the collision, saw Titanic's flares but failed to assist. Around 4 am, RMS Carpathia arrived on the scene in response to Titanic's earlier distress calls. The disaster was met with worldwide shock and outrage, both at the huge loss of life and at the regulatory and procedural failures that had led to it. Public inquiries in Britain and the United States led to major improvements in maritime safety. One of the most important results of the inquiries was the establishment in 1914 of the International Convention for the Safety of Life at Sea (SOLAS), which still governs maritime safety today. In addition, there was an effort to learn from the many missteps in wireless communications that had increased the number of fatalities, and as a result, several new wireless regulations were put in place around the world.

Table 1 shows a list of more recent disasters for which situational awareness data was available through social media, in particular Twitter. We wanted to see if we could learn anything by applying data from actual disasters to our Emergency MANET simulation. We were hoping to find more specific data regarding the stranded victims (such as location data) or the disaster itself which would allow us to perform a more realistic simulation and thereby validate the proof of concept of using a mobile ad-hoc network. We decided to use the location data for the New South Wales (1) (NSW) wildfire disaster (see Table 1) with the dates of October 8, 2013, and November 1, 2013, from the Dryad Dataset.

We were able to import a representative sample of the GPS locations of NSW wildfire disaster into our emergency manet simulation. For simplicity the simulation kept the initial locations of the victims fixed; however, we added three rescue workers that were mobile. The initial location of the mobile rescue workers was calculated using the minimum location in x and maximum location in y of the fixed nodes. The simulation had the mobile devices operate in listening mode until they received a signal from a rescuer. The mobile device would only send a signal back when the rescuer was within a certain distance. We carried out a battery drain attack simulation, where we randomly generated different battery levels for each device. Then, we used a modified version of the battery remain formula in the framework for maximum survivability routing for wireless MANET developed by Marbukh & Subbarao (2000) to calculate the remaining battery of the mobile device after each time that a signal was sent. In this framework, the remaining battery life equals the remaining battery power divided by the future power-draining rate.

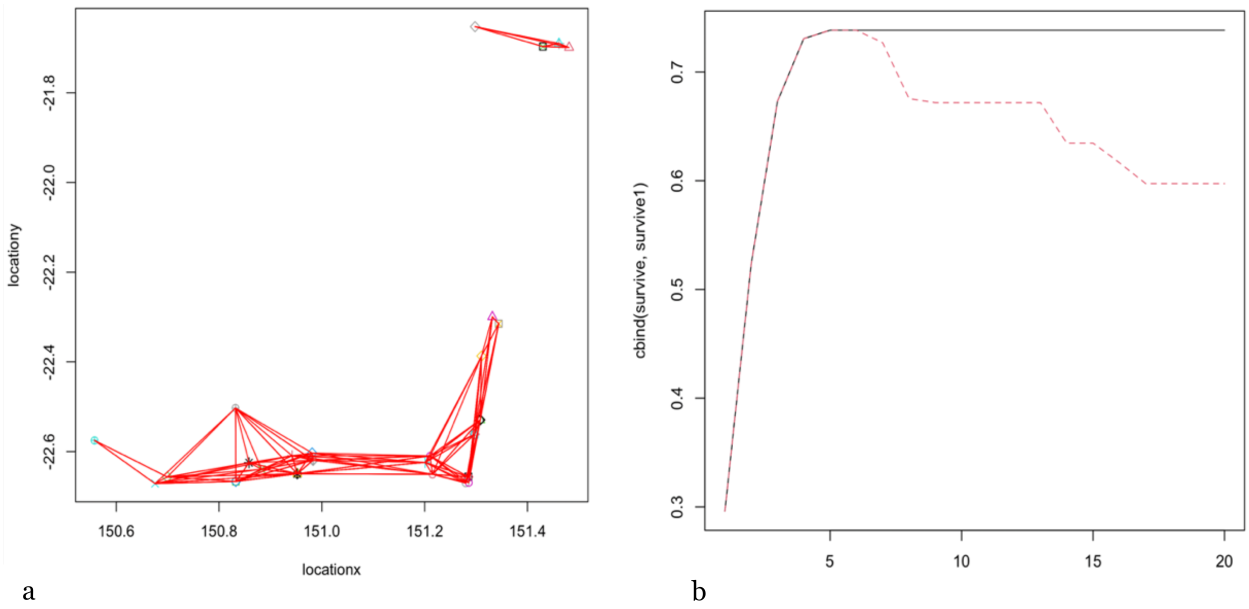

Figure 4: NSW Wildfire (2013) Emergency MANET simulation

6.0 Result of NSW Wildfire MANET Simulation

The result of the NSW Wildfire MANET simulation is shown in Figure 4. This modified simulation was done in an attempt to create more realistic results to validate what we observed in the original simulation. For the NSW wildfire simulation, the geolocation derived from victim's twitter messages was used to determine the location of the victims in the simulation as seen in Figure 4(a). It can be seen that the locations of impacted individuals in Figure 4(a) is more tightly clustered compared to the original simulation which assumed a uniform distribution. This would be expected in densely populated areas like in the 2011 tsunami in Japan. However, in other cases the nodes are likely to be less clustered or perhaps in smaller separated clusters like the 2018 wildfire in northern California (Wikipedia, Camp Fire) (Figure 6(b)). It also appears that a natural disaster could lead to more clustering of the victims as they avoid areas of active danger. Clustering will tend to enhance the operation of an emergency MANET. Less power will be needed to transmit thereby increasing the probability of a distress message getting through to rescue workers.

Disaster events can take place over several hours or several days. Cell phone or mobile device power will not usually last more than a day if lightly used. Also, these events can take different amounts of time as the events can unfold over several hours or several days like the NSW case. It is assumed that there is no charging of the mobile devices after the disaster. Figure 4(b) shows a comparison between the fully charged device broadcasting at full power (solid line) and the device that is steadily discharging (dashed line). In the original simulation (Figure 3(b)) the mobile device discharges more rapidly. This improvement is a result of the higher density of the mobile devices requiring less power to send the distress messages.

The longer term impact of the power drain is shown in Figure 5. After perhaps 3-4 hours the devices have reduced transmit range as illustrated by Figure 5(a) which shows the devices at low power. After perhaps 8-12 hours the devices are at very low power, unable to communicate with even the closest devices (Figure 5(b)). At this point it makes little sense for the mobile device to continue transmitting. Once the battery reserve of the mobile devices starts getting very low (perhaps around 10-20%) it might be better for the device to go into a power-saving hibernate mode and wait for the rescue workers to come within range. The device then operates in listening mode until a signal is received from a rescuer. The device would only send a signal back when the rescuer was within a certain distance based on the GPS location information.

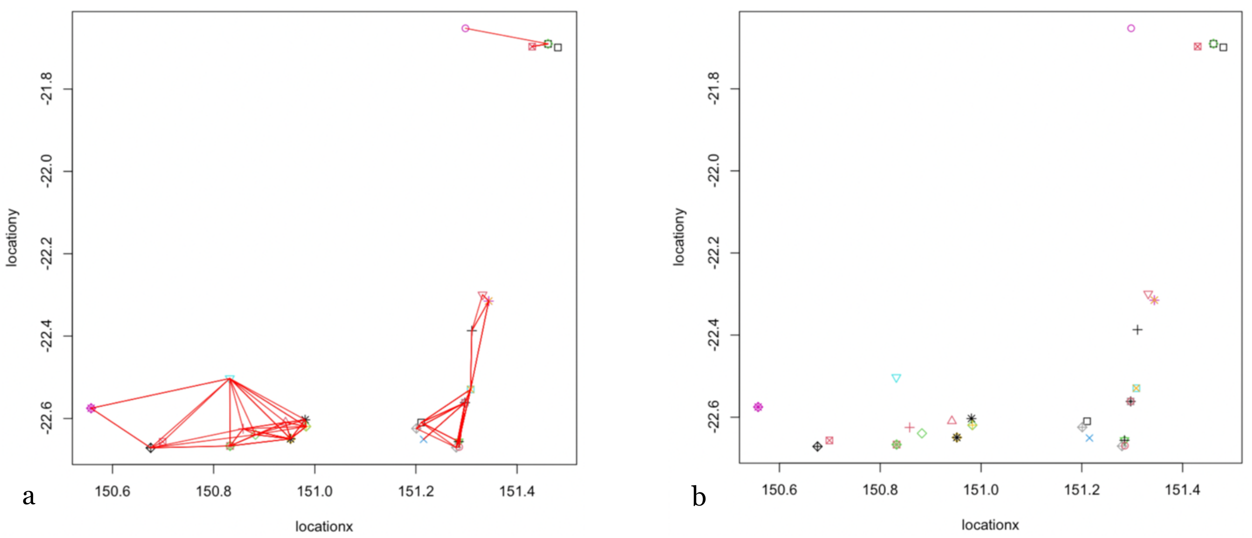

Figure 5: NSW MANET simulation for 5(a) low power 5(b) very low power

7.0 MANET Communication Protocol Design and Optimization

Availability of situational awareness data is extremely important for the emergency MANET. Decisions need to be made on the best available data. If the available data is outdated or incomplete it will lead to the possibility of sub-optimal decisions being made with undesirable consequences. For the emergency MANET, it is important that the existence of a stranded individual and their location be relayed to the central command and control center. Since availability of GPS information is critically important to this application, broadcast routing is used. This is done even though there can be severe power constraints. The simulation results in Figure 4 have already taught us one valuable lesson: the traditional broadcast routing can be modified in a simple way to dramatically improve the chance that the distress signal from a device is received by the command and control center. Traditional broadcast routing only transmits each message once to avoid flooding. However for an emergency manet each node should continue retransmitting every received distress signal until an acknowledgement is received from central control.

Cell phones can survive a day or two under lightly utilized conditions. However, a natural disaster such as an earthquake or tsunami can strike at any time without warning and a cell phone could be low on charge. The system should be designed to make optimal use of available power. Transmit power should be adapted by the mobile device based on battery reserve to preserve energy as much as possible. In case of low power, the device should listen for packets from other devices and use the strength of those signals and the remaining battery power to determine the power to broadcast the information. The command center should send an acknowledgement packet to a node when it detects a distress signal. If the acknowledgment is not received, the device should retry, perhaps at a higher power level, if possible. If the acknowledgement is received, the device should stop transmitting its distress signal so save energy. Also, the device should not transmit too frequently unless it detects that its GPS location has changed. Some power should also be reserved so the device will be able to respond in the event that it takes more than a day for the rescue workers to gain access to the areas where potential survivors might be found. Then, once on the location, a mobile ad-hoc network can be used to guide rescuers to where people could be and to the general areas where they should focus their rescue and relief efforts.

Users of Emergency MANETS must be willing to risk some privacy in exchange for the benefits they receive. For the Emergency MANET, individuals could be identified by cellular phone number. However, to make the system more acceptable it may be desirable to anonymize the identity of the individual. Individuals in Emergency MANETS may opt out or may opt to suppress their phone number for privacy reasons. This could be done by randomly choosing a user ID based on the SHA-1 hash of their current location and time. This preserves the identity of the individual as there is no information to identify the user.

Figure 6. (a) Location of Titanic Sinking (b) Satellite Photo of the Camp Fire (2018) (from Wikipedia)

8.0 Summary and Conclusions

Emergency MANETs can be used to set up communication and information interchange capability in an environment where it may not be possible to deploy a traditional network infrastructure in a timely manner. We used a simulation of an Emergency MANET to gain insight into how to optimize the communication protocol of mobile devices to share situational awareness information to improve the probability of survival of stranded victims. The technique we used was a Markov chain simulation of sending distress messages containing the GPS location of cellphones using broadcast routing. Assuming an isotropic radiation pattern we used the inverse square of the Euclidean distance between nodes to determine the probability of a message getting through on any single attempt for the Markov chain analysis. We performed two simulations: a baseline case with random uniformly distributed nodes and an actual case using twitter geolocation from the New South Wales wildfire disaster of 2013 (Wang, 2017). Both simulations gave similar results however we observed in the NSW wildfire disaster the geolocation of the victims was rather tightly clustered which allowed for the mobile devices to transmit distress messages while maintaining more of their initial battery life for longer. Our overall conclusion from the simulations was that the communication protocol should be optimized for cellphones with low remaining battery power. Natural disasters often strike with little or no warning and victims have precious little time if any to charge their cellphones. We observed that a minor change in the broadcast routing protocol could significantly enhance the overall survival rate by aggregating and retransmitting all previous messages instead of retransmitting individual messages as they are received. A number of other methods for maximizing victim survival rate through communication protocol optimization were discussed. Most of these were based on power management techniques such as maintaining a reserve power in case a rescue team came within close range of a victim after an extended time period. The use of situational awareness data can help improve the effectiveness of rescue efforts in natural disasters and the use of an Emergency MANET could help provide some of that information. All of these disparate sources of information together can improve future search and rescue efforts by allowing for more efficient use of the limited resources available and ultimately saving more lives.

Acknowledgements

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