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A Performance Comparison of Wireless Multi-Hop MAC Protocol for Emergency Networks

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***Abstract*— Recent disasters like hurricanes, tsunamis, earthquakes, and the threat of pandemics are managed by wide range of technologies such as computer, telecommunications, and trend to integrate comprehensive sensor applications. In these days, Communication Structures and Management to rescue survivors from any emergency situation have become an area of interest. In this paper, the application of Wireless Multi-hop Multiple Access Control (MAC) Protocol Emergency Networks has been discussed. Here we have carried out a simulation for the analytical part where Tree splitting is used as a MAC Protocol for both the Single-hop and Multi-hop approach. In comparison, it is showed that Multi-hop outperforms the Single-hop in terms of time and energy efficiency. In this paper we have taken a threshold value of range defined as the ratio of the coverage radius of the Base station to that of the Mobile Unit. Under this threshold, it is better to use the Multi-hop than the Single-hop. In addition, simulation results keep track of the percentages of isolated survivors who fail to make contact to the base station due to the absence of any path from individual survivors to the base station.**

***Keywords*—** *Multiple Access Control (MAC), Emergency Networks, Survivors, Tree Splitting, Single-hop MAC, Multi-hop MAC*

I. INTRODUCTION

A disaster is an unpredictable phenomenon. Recently, emergency communication infrastructures for disaster management have become an area of interest for a number of researchers. Most works on emergency networks assume known mobile unit identities. This assumption is reasonable for emergency networks for workers in the same factory, or subscribers of the same cellular phone services. Under this case, MAC can be possibly done in advance. For example, transmission resources such as Time Division Multiple Access (TDMA) time slots or Code Division Multiple Access (CDMA) codewords can be preassigned to individuals before the disaster takes place, as in [1] and [2] . However, in a general case, survivors' unit identities are not known in advance. In such cases, there is a problem for survivors' first contacts to the BS. Once the survivors made their first contacts, a known MAC technique can be used for later transmissions from survivors. There are several MAC techniques for wireless ad-hoc networks that are relevant. They can be found in [3] and [4]. In [5], the authors proposed a simple MAC protocol for multi-hop wireless ad-hoc networks for first contacts from survivors in disaster areas. It was demonstrated through approximated analysis that the multi-hop protocol is more energy and time efficient than the single-hop protocol. However, no simulation performances were given to verify the accuracy of the analysis. Therefore, in this research, we shall investigate the protocol performances through simulations.

II. EMERGENCY NETWORKS

Disasters can occur any time without prior warnings due to our inability to form accurate predictions. Disasters like the September 11 attack in 2001, the Tsunami in December 2004, Hurricane Katrina, earthquakes, and floods can happen all of a sudden and cause a lot of damages. If a disaster destroys communication infrastructures, it can isolate a survivor by preventing him or her from contacting other people, greatly hampering immediate relief and rescue efforts. As such the stress on emergency networks evolved, attention is drawn to the use of wireless technologies in order to locate survivors [6]. Emergency networks can be the basic hardwares that allow emergency relief team members to talk with one another and coordinate their efforts. We can classify emergency network situations into two types as described below.

A. Pre-Disaster Emergency Networks

Pre-disaster emergency networks operate before a disaster takes place. In this scenario, the main objective is to send out warnings with the help of different transmission media. While we expect that the wireless media will play a vital role for such communications, transmissions of warnings can also be wireline, or a mixed of both wireline and wireless media. A warning message may have to travel through different types of transmission systems described in figure 2.1. To send out warnings quickly, we need to provide an overall system architecture and protocol that allow warning messages to travel across different types of transmission media.

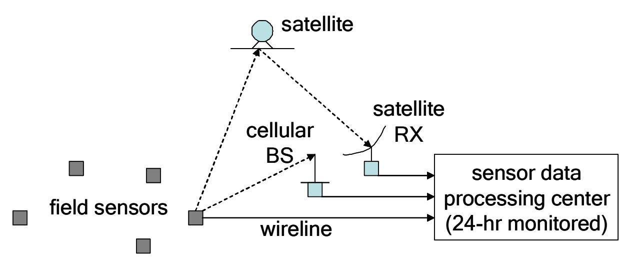

Fig 2.1: Transmissions of data from sensors to the processing center [7]

Communications for disaster warnings have two parts. The first part is from the various sensors in the field to the data processing center. The second part of the pre-disaster communications is sending out warnings to individuals. To maximize the chance of successful warnings, we expect that all kinds of transmission media will be used, as shown in the figure 2.1 and figure 2.2.

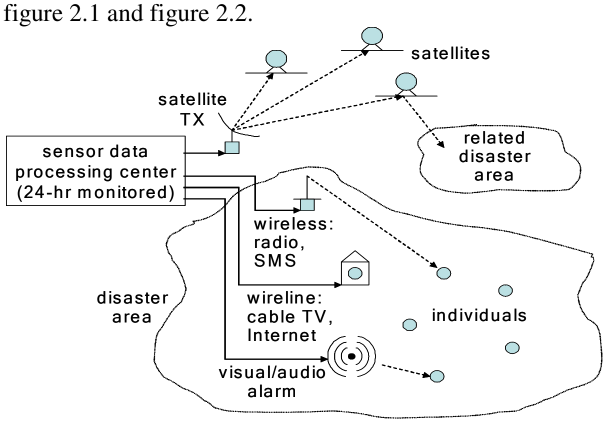

Fig 2.2: Sending warning signals [7]

B. Post-Disaster Emergency Networks

Post-disaster emergency networks operate after a disaster occurs. In the worst case, all communication systems in the affected areas are completely destroyed; survivors cannot contact the rescue team through normal communications. To assist the rescue team in locating survivors, emergency networks can be set up quickly. In particular, the rescue team may set up several temporary base stations (BSs) to communicate with the survivors. It is assumed that the survivors have some types of mobile devices that can contact these BSs. Examples of such devices are cellular mobile handsets, RFID Badges, and PDAs [6]. In addition, it is assumed that these mobile devices have limited but sufficient amount of power left to give the trace of their locations to the BSs. At present, the radio communication systems used by emergency personnel in most communities are not fully "interoperable"--that is, various divisions, ranging from police and fire departments to government officials, communicate on different frequency bands and are often not able to connect with one another.

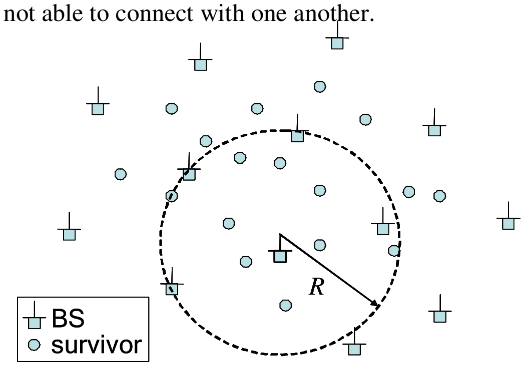

Fig 2.3: Coverage areas of BSs cover all survivors the coverage radius of a BS is denoted by R [5]

In a statistics from a June 2004 report by the U.S. Conference of Mayors [8] , it was found that 94 percent of the 192 cities surveyed do not have interoperable capability among their transportation departments. In [5], the authors assume the worst case scenario in which a disaster completely destroys all communication infrastructures. Once the disaster has happened, the rescue team would set up temporary BSs at strategic locations such that their coverage areas cover the whole disaster area, as shown in figure 2.3. In addition, it is assumed that survivors' mobile devices possess the interoperable capability within the areas of emergency networks. Using an emergency communication protocol, the BSs can communicate with the survivors' mobile devices, enabling the rescue team members to exchange useful information with the survivors. However, since the rescue team cannot know in advance who the survivors will be, there is a problem of initializing the communication process in such an emergency network [5], the authors compared single-hop and multi-hop MAC protocols for initialization of contacts from survivors. Through approximated analysis, it was shown that the multi-hop protocol is more energy efficient as well as more time efficient when the ratio of the coverage radius of the BS to that of a survivor's mobile device is large, i.e., large number of hops required. The multi-hop approach implies that the network operates as a wireless ad-hoc network.

C. Wireless Ad hoc Networks

Among various requirements in the next generations, wireless communication system is a need for rapid deployment of independent mobile users. Examples include establishing an emergency network for rescue operations and disaster relief efforts. Typically, emergency/rescue communications is centralized; the network operations depend on proper functioning of the central controllers. If the centralized infrastructure were to fail due to a disaster or any other reason, the network would collapse. Hence, advances in wireless communications should aid in making emergency preparedness systems and disaster relief networks that are robust, autonomous, and provide reliable and secure communications.

Rescue operations and disaster relief scenarios cannot rely on centralized and organized connectivity. An attractive approach for such communications is based on wireless mobile ad hoc networks. An ad-hoc network is an autonomous collection of mobile nodes that communicate over relatively bandwidth-constrained wireless links. Each node is equipped with wireless receiver and transmitter using antennas that may be omni-directional, highly directional, or possibly steerable. Since nodes are mobile, the network topology may change rapidly and unpredictably over time. If the network is decentralized, all network activities including topology discovery and delivering messages must be executed by the nodes themselves. A wireless ad hoc network for emergency communications may operate in a stand-alone manner or be connected to a larger network. Sizes of wireless ad hoc networks are diverse, ranging from small and static networks that are constrained by power sources to large-scale mobile and highly dynamic networks. The design of communication protocols for these networks involves several complicated and challenging issues. An emergency telecommunication network should be able to adaptively select routing paths to alleviate any of the effects such as wireless link quality, propagation path loss, fading, multiuser interference, power expended, and topological changes in order to maintain the performance and dependability of the network [9]. In an emergency scenario, power may be supplied to static nodes through a generator, while mobile nodes operate on battery power. Therefore, a vital issue for emergency ad hoc networks is to conserve power while still delivering messages reliably, i.e., achieving a high packet transmission success rate. This can be accomplished by altering the transmitter power of the mobile nodes to use just the amount needed to maintain an acceptable signal-to-noise ratio at the receiver. Reducing the transmitter power allows spatial reuse of the channel frequency and thus increases the network throughput [10]. Using power control in an emergency situation mitigates the multiuser interference since a transmission will not interfere with as many nodes. This will increase the number of emergency or rescue mission nodes that may communicate simultaneously. Altering the transmission power also reduces the amount of interference to other emergency networks or any other wireless networks operating on adjacent radio frequency channels. In networks where nodes operate on battery power, e.g. hand-held radios used by rescue workers, conserving power is crucial since battery lives determine whether a network is operational or not. For certain emergency applications, e.g. hostage situation and terrorist attack, it is desirable to maintain a low probability of intercept and/or a low probability of detection [11]. Hence, rescue mission nodes would prefer to radiate as little power as necessary and transmit as infrequently as possible, thus decreasing the probability of interception and/or detection. For emergency management, ad-hoc networks are easy to deploy, require short set-up time, and do not rely on any existing communication infrastructure. As the wireless transmission range is limited, packets may be lost due to the mobility of nodes. The constraint on battery lives poses a problem of designing communication protocols with low energy consumption. In addition, the ease of snooping on wireless transmissions creates a potential security hazard. Over all, the deployment of ad-hoc networks involves a number of technical challenges, including the design of MAC protocols which is the focus of our research.

D. *MAC Protocols for Ad-Hoc Networks for Emergency Management*

Knowledge of Survivors' Identities: Most existing works on post-disaster emergency networks assume known identities of potential survivors. This assumption is reasonable regarding emergency networks for workers in the same factory, subscribers of the same cellular phone service, and personnel deployed in a military operation. In these cases MAC can possibly be done in advance as mentioned earlier. We can assign TDMA time slots in a TDMA system or CDMA code words in a CDMA system to individuals in the pre-disaster case [1] and [2].Consider instead a post-disaster situation where the survivors' identities are not known unless until they are reported to the rescue team through the BSs of an emergency network. In [5], the authors pointed out a problem of initializing the communication process in such an emergency network. Their proposed protocol can be considered as an initial phase of MAC. During this phase, survivors' identities as well as locations can be reported to the rescue team. Once the initial phase has completed, we can use other known MAC techniques for the case of known survivors' identities. For known survivors or nodes, there are several known MAC techniques for wireless ad-hoc networks [3] and [4].

Single-Hop MAC for Contacts from Unknown Survivors: In this case, survivors try to contact the BS in a single hop. For energy efficiency, each survivor tries to contact the nearest BS [5]. When a BS broadcasts a message, it also sends out information about its location. From these messages, a survivor can find out the location of the closest BS. To deal with the interference problem, we can use different CDMA code words for different BSs. Since we do not expect a large number of BSs, these CDMA code words can be made known in advance as a part of an emergency communication protocol. In the single-hop case, the MAC problem in a single BS coverage area is almost the same MAC problem for a broadcast network. One main difference is the so called hidden node problem [12], the message transmitted by one survivor is heard by the BS but not by another survivor on the other side of the coverage area.

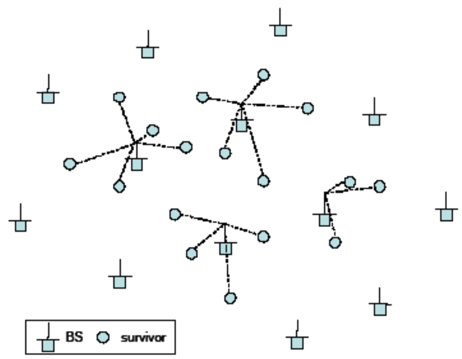

Fig 2.4: Self-assignment of survivors to BSs [5]

A hidden node is a node which is out of range of a transmitter node (node A in figure 2.5), but is in the range of a receiver node (node B in figure 2.5). A hidden node (node C in figure 2.5) does not hear the message sent from a transmitter to a receiver. When node C transmits a message to node D, the transmission collides at node B with the message from node A to node B. In this case, we say that node C is hidden from node A. Obviously, the presence of hidden nodes leads to higher collision probability. In general, the probability of successful transmission decreases as the distance between source and destination increases and/or the traffic load increases [12].

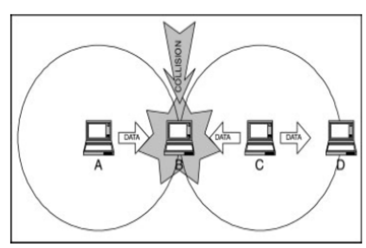

Fig. 2.5: Illustration of the hidden node problem [4]

Among known contention-based MAC techniques, the authors in [5] selects the use of tree splitting for simplicity in analysis. Since there is a potential in performance improvement from using other MAC techniques, we shall briefly review common MAC protocols for broadcast networks, and then focus on tree splitting later.

E. Nature of Broadcast Networks

In broadcast networks each station is attached to a transmitter/receiver which communicates over a medium shared by other stations. So transmission from any station is received by other stations. There are no intermediate switching nodes. An example of broadcast network in use today is an Ethernet local area network. The main problem for broadcast networks is dealing with collisions among multiple users or nodes. If more than one user transmits at a time on the broadcast channel, a collision will occur. The multiple access control (MAC) problem deals with how to manage the transmissions from multiple users. Protocols that solve the MAC problem are called MAC protocols. MAC protocols for broadcast networks can be divided into two classes: contention-based and reservation-based. Contention-based protocols resolve a collision after it occurs. These protocols execute a collision resolution mechanism after each collision. On the other hand, reservation-based or contention-free protocols ensure that a message collision never occurs through advanced reservation of transmission resources by the nodes. Since we are interested in scenarios in which survivors' identities are unknown, only contention-based protocols are relevant. Therefore, we shall focus on contention-based protocols. Tree Splitting is discussed here among the contention based protocols Aloha, Slotted Aloha (S-Aloha), Carrier Sense Multiple Access (CSMA), CSMA with Collision Avoidance and CSMA with Collision Detection.

Tree Splitting: For tree splitting, if multiple nodes transmit at the same time, i.e., collide, these nodes will randomly split themselves into two sets [7] . Those in the second set will wait until all the collisions in the first set are resolved before transmitting again. In figure 2.6, three nodes A, B, and C collide. The first split separates A from B and C. After A transmits, B and C collide. The second split happens to be unfortunate with no one in the first set. After an idle slot, B and C collide again. The third split separates B and C, giving two successful transmissions.

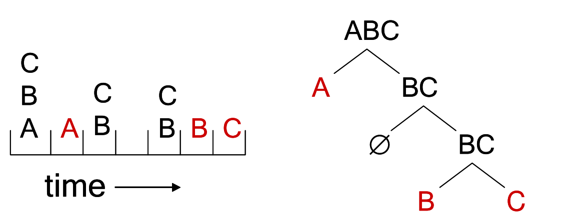

Fig. 2.6: Tree splitting for broadcast networks [7].

In [5], tree splitting is used for a single-hop MAC protocol for a single BS coverage area in an emergency network with some modifications to solve the hidden node problem as described next. Assume that time is divided into slots. For the hidden node problem, the BS sends an acknowledge packet in the same time slot informing a success, an idle slot, or a collision. In addition, assume that there is a good estimate of the survivor density per unit area. With this knowledge, the BS can estimate how many survivors are in its coverage area. The single-hop MAC protocol starts with the BS broadcasting a message to ask survivors' mobile units to split into several groups with slightly greater than 1 person per group. Then tree splitting is used to resolve collisions within each group, from the first group to the last group.

Multi-Hop MAC for Contacts from Unknown Survivors:

In the multi-hop protocol proposed in [5], it is assumed that the survivors' units have the same coverage radius r that is strictly less than the BS coverage radius R. To conserve energy in mobile units, transmit power is kept small. As a result, uplink transmissions require relaying, as illustrated in figure 2.7. As such, uplink transmissions operate in a multi-hop mode, while downlink transmissions from the BSs are broadcast in a single-hop mode.

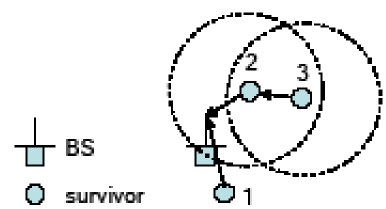

Fig 2.7: Relay transmission for mobile unit 3 [5]

For multi-hop transmissions, the authors also assume that there is always a path from a survivor to the BS. The basic ideas of the proposed multi-hop MAC protocol are as follows. A survivor's unit that can reach the BS in k hops is called a k-hop unit. In the first round of the protocol, the BS tells all 1-hop units to contact itself. In the k^{th} round of the protocol, the BS assigns a subset of $(k-1)$-hop units to act as parents. A parent will serve as a temporary BS for its neighbors to contact using tree splitting, as illustrated in figure 2.8. A parent then aggregates children's information and passes it to the BS. The process repeats until all units are covered. The algorithm process can be picturized by considering the area that covers all units that already contacted the BS. This area will increase round after round until all survivors' units are covered.

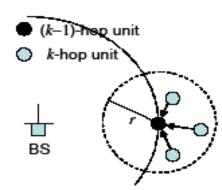

Fig. 2.8: A set of k-hop units and their (k – 1)-hop parent in round k [5]

If parents are far enough apart so that their coverage areas do not overlap, they can operate simultaneously. One important aspect of the multi-hop protocol is the ability of having multiple successful contacts at different parents in a single time slot. In case of a single-hop protocol in which everyone tries to contact the BS, there is at most one successful contact in each time slot. Having possibly multiple successful contacts is what makes the multi-hop protocol more time-efficient.

III. METHODOLOGY

In our simulation, the disaster area is considered as a circle including a single base station with coverage radius, R = 5000m. Survivors are randomly located in the disaster area according to the uniform distribution.

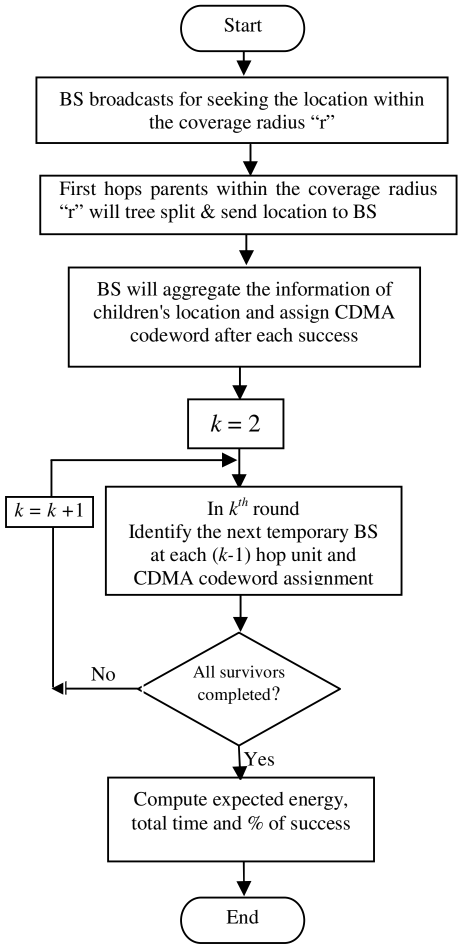

Fig. 3.1 : Flow chart showing BS Activity

Assume that this mobile unit (MU) has enough power to last until the protocol terminates. The coverage radius of each MU denoted by ‘r’, is a variable that will be adjusted in the simulations. The MAC protocol for first contacts from survivors is taken from [5], where tree spitting is used to resolve contentions among multiple survivors. At first, simulations are carried out for the single hop MAC protocol for first contacts from survivors. Then, multi-hop MAC protocols are simulated for different values of ‘r’ ranging from 500m up to 5000m. In each scenario, the simulation lasts until either all survivors have successfully contacted the BS or no more survivors make contact in the last round of protocol. To obtain numerical results for protocol performances simulations are performed 20 times in each scenario. For simulations, two different numbers of survivors in the disaster area are used: 500 and 100 survivors. Figures 3.1 and 3.2 show the simulation flowcharts for the multi-hop MAC protocol. Figure 3.1 covers the operation of the BS while figure 3.2 covers the operation of a MU.

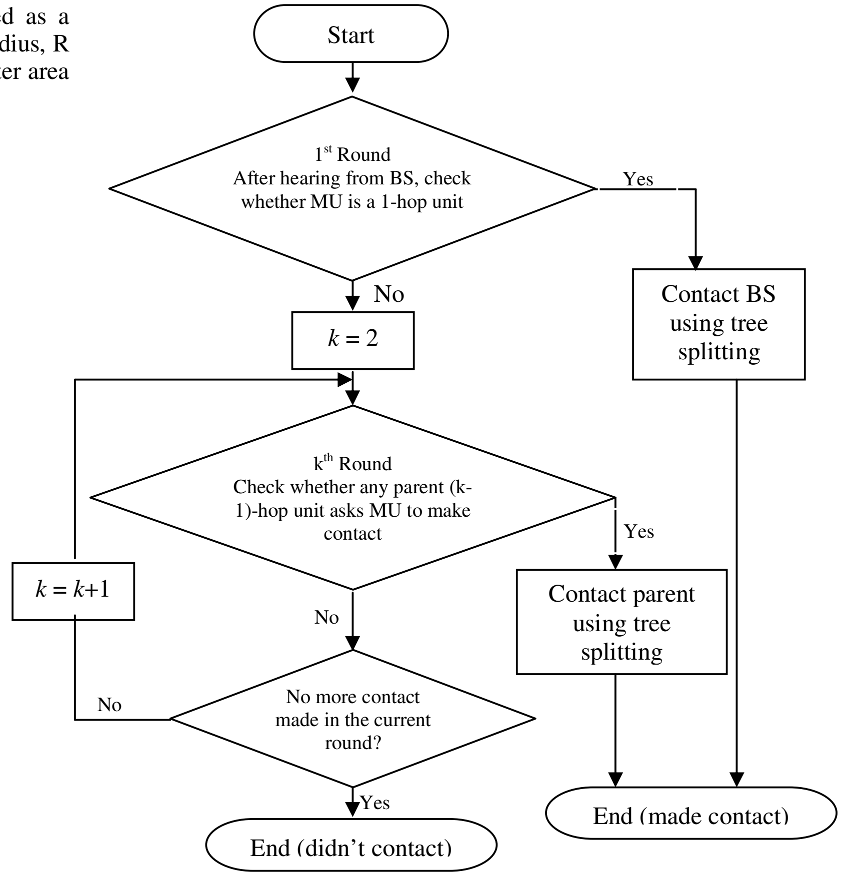

Fig. 3.2 : Flow Chart showing MU activities

IV. RESULTS AND DISCUSSION

From simulations, we shall use two performance measures that were also considered in [5]. The first performance measure is the maximum energy usage by the survivors’ units. The second performance measure is the total time taken for all survivors’ successful contacts to the BS. In addition to the above two performance measures, we shall also measure the percentage of survivors that have no path to the BS and thus cannot successfully make contact. Note that if the coverage area of the survivor’s unit does not contain the BS or any other survivor’s unit, then that survivor cannot reach the BS. Note also that these isolated survivors were not considered in [5].

Figure 4.1 shows the survivors’ locations and the resultant tree structure of the multi-hop protocol for R = 5000m and MU coverage, r = 825m with number of survivors to be 500. In figure 4.2, we considered R = 5000m and r = 525m with the same number of survivors as in the figure 4.1. So when the coverage radius of the MU decreases below a certain value (r = 525m), the Multi-hop protocol does not support successful contacts for all survivors. Hence, there are isolated survivors as some of the MUs are uncovered. “+” indicates the survivors location and the connecting lines indicate the successful contact to BS. Isolated survivors are indicated as “+” without connecting lines.

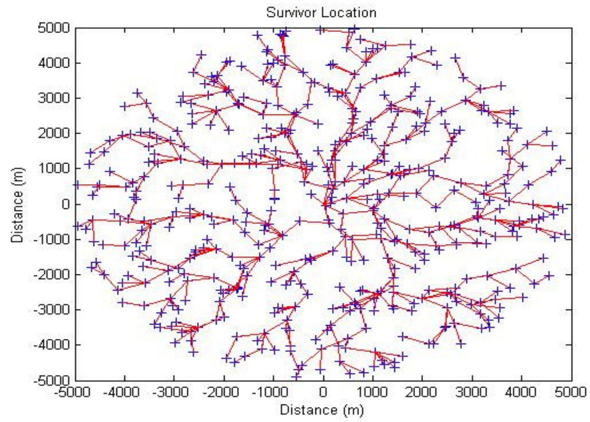

Fig. 4.1: Survivor locations and Tree structure for multi-hop protocol (R = 5000m; r = 825m; Number of Survivors = 500)

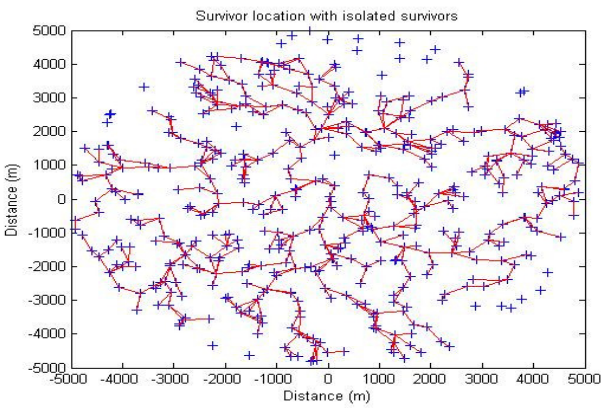

Fig: 4.2 Survivor locations with isolated survivors (R = 5000m; r = 525m; Number of Survivors= 500)

Figure 4.3 shows the energy comparison between Multi-hop and Single-hop with respect to coverage ratio R/r. Here, number of survivors = 500 is considered. It explains, when the BS coverage is less than two times the MU coverage, the Single-hop is outperforming the Multi-hop protocol in terms of energy. Almost the same scenario of 500 survivors described in figure 4.4 when number of survivors is 100. Here, E_{multi} indicates the Energy Usage in Multi-hop approach and E_{single} indicates Energy Usage in Single-hop approach.

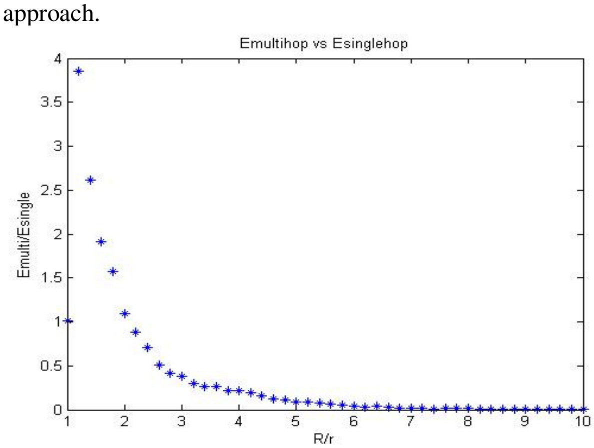

Fig: 4.3 Compariosn of Energy efficiency (R= 5000m; r varies from 2500m to 500m; Number of Survivors = 500)

The figure 4.5 shows the total time for all the survivors' contacts between Multi-hop and Single-hop with respect to coverage ratio R/r. Here number of survivors is 500. It shows that the total time required for Multi-hop case is always less than that of the total time required for the Single-hop case. The same scenario of 500 survivors is described in figure 4.6 when number of survivors is 100. Here, T_{multi} indicates the Time Usage in Multi-hop approach and T_{single} indicates Time Usage in Single-hop approach.

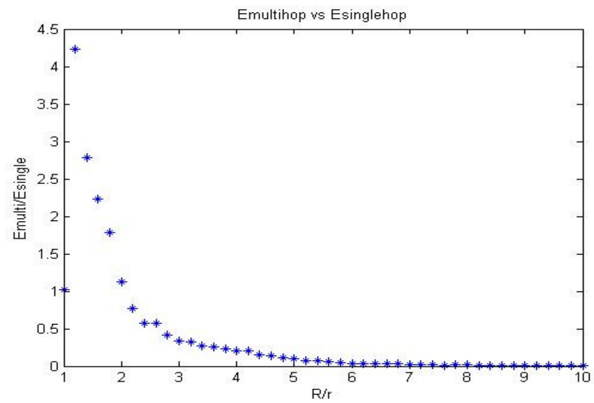

Fig: 4.4 Compariosn of Energy efficiency (R= 5000m; r Varies from 2500m to 500m; Number of Survivors = 100)

Figure 4.7 shows the percentage of survivors with successful contacts with respect to the R/r ratio. It demonstrates that when the ratio R/r is increasing the percentage of success rate is going down because when R/r is increasing i.e. r is decreasing there is a reduction of the overlapping area hence the number of isolated survivors increases. The above phenomenon is clearly shown in figure 4.8. It shows further that when the number of survivors is very high, the number of parents is very high i.e. overlapping will be high, so isolated survivors will be decreasing. It can be said that the density of survivors have significant impact on the percentage of isolated survivors so the curve is decreasing after some specific point (for R/r=4 and for 500 users). If the number of survivors are more than 500 then the curve will decrease after some more value of R/r.

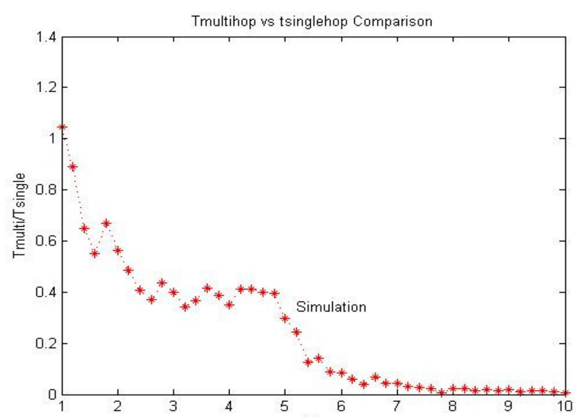

Fig: 4.5 The ratio T_{multi}/T_{single} as a function of R/r (R= 5000m; r varies from 2500m to 500m; Number of Survivors = 500)

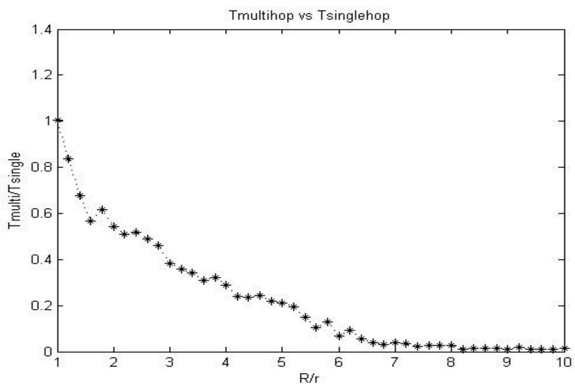

Fig: 4.6 The ratio T_{multi}/T_{single} as a function of R/r (R= 5000m; r varies from 2500m to 500m; Number of Survivors = 100)

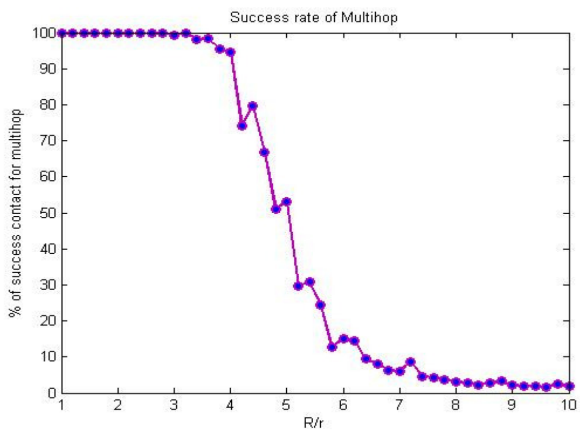

Fig: 4.7 Percentage of Successful contacts (R= 5000m; r varies from 2500m to 500m; Number of Survivors = 100)

Additionally in figure 4.8 for specific number of R/r ratio, the number of survivors increased from 25 to 500 with the increment of 25. From each number of survivors, average percentage of successful contacts is calculated from the simulation program for a specific R/r (R/r= 1 to 7).

Figure 4.9, the time comparison curve shows that the simulation work is almost same with the analytical work with some little deviation. This deviation can be because of some delays or idle periods taken while tree splitting. Here, Tmulti indicates the Time Usage in Multi-hop approach and Tsingle indicates Time Usage in Single-hop approach.

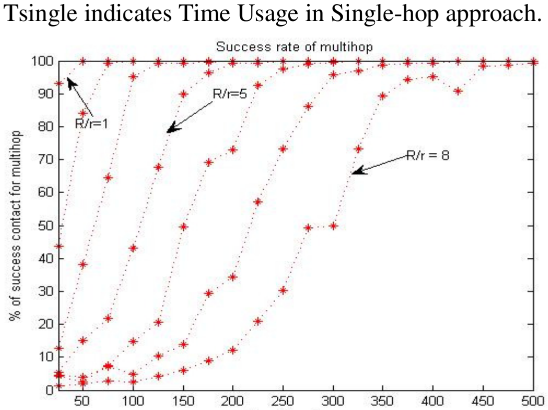

Fig: 4.8 For different R/r ratio, Percentage of Successful Contacts vs No. of survivors

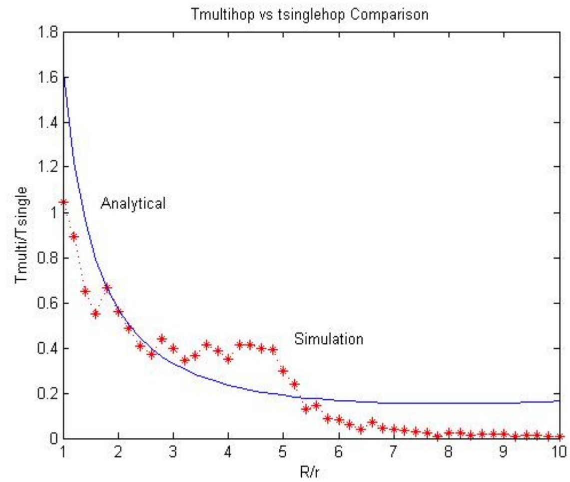

Fig: 4.9 Comparison of Time efficiency: Analytical work with the Simulation results (R= 5000m; r varies from 2500m to 500m; Number of Survivors = 500)

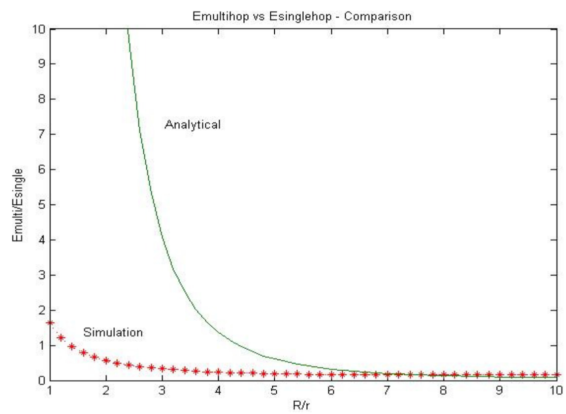

Fig: 4.10 Comparison of Energy efficiency : Analytical work with the Simulation results (R= 5000m; r varies from 2500m to 500m; Number of Survivors = 500)

Figure 4.10 shows that the simulation work in case of energy comparison is almost the same with the analytical work with little deviation. This deviation can be because some survivors already made contacts, so upper bound on the energy. Here, E_{multi} indicates the Energy Usage in Multi-hop approach and E_{single} indicates Energy Usage in Single-hop approach.

V. CONCLUSION

The analytical work done in the paper "MAC Protocol for Contacts from Survivors in Disaster Areas Using Multi-hop Wireless Transmissions" is verified with the simulation.

The simulation shows almost the same results as

i) expected total connection set up time obtained by the multi-hop protocol is less than the single hop protocol
ii) reduction in the expected minimum energy usage in the multi-hop compared to the single-hop .

It can be seen from the results that for both the scenarios of 500 and 100 survivors the expected energy usage and the total connection setup time is almost the same.

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