LEVY WALK MODELS OF SURVIVOR MOVEMENT IN DISASTER AREAS WITH BARRIERS

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ABSTRACT

Disasters are catastrophic events that occur unexpectedly in a random manner. It is important that when a disaster occurs, the victims in the disaster area are rescued quickly to avoid massive casualties. Disaster areas may leave victims bereft of food, water, shelter and medical help. The goal of the work outlined in this paper is to study the movement of survivors towards rescue devices when barriers are involved. Barriers are obstacles that prevent both survivors and crewmembers from moving freely in a disaster area thereby slowing down rescue operations. It would therefore be necessary to study movements of survivors with barriers included in the simulations so as to produce more realistic results to be used when rescuing survivors in disaster areas.

KEYWORDS

Levy walk, Levy flight, random walk, search and rescue network, power-law distributions

1. INTRODUCTION

In recent times, many disasters have occurred and there were survivors that needed to be rescued in time so as to avoid major casualties. The disasters range from terrorist attacks, which are man-made disasters, to natural disasters such as earthquakes and tsunamis. Examples of such recent disasters include the Indian Ocean tsunami of 2004, Hurricane Katrina of 2005 in the Gulf Coast of the US, the Haitian earthquake of 2010, the Hurricane Sandy of 2012 in the Mid-Atlantic Coast of the US, and the recent Typhoon Haiyan that hit the Philippines on November 8, 2013.These disasters remind us of the need to have reliable disaster recovery and relief operations. These operations will have to be planned ahead of time to increase efficiency of rescuing survivors with the availability of reliable communication networks. A disaster recovery network should be able to provide assistance to both the disaster victims and the rescue crewmembers.

Presently, this process is carried out manually, which is very time consuming because it is usually an ad hoc solution that requires many people to be deployed in a very short time to search for survivors. To improve the efficiency of the process, a mechanism needs to be developed that involves the survivors reporting their locations to a Command Center thereby making it easier for crewmembers to be able to locate survivors quickly. This mechanism is a disaster recovery network that needs to be an ad hoc wireless network that can rapidly be deployed in order for the

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crewmembers to be dispatched to a disaster area within a short period of time after the disaster has occurred.

In this paper we consider an ad hoc wireless network for disaster recovery in which survivors are required to walk toward beeping devices that are randomly dispersed throughout the disaster area. Once a survivor reaches any one of these devices, they are certain to be rescued. The network is an extension of the Portable Disaster Recovery Network (PDRN) [1, 2]. While PDRN is designed for situations where survivor movement is not hampered by obstacles, the current network assumes the existence of obstacles along the paths taken by survivors to reach a beeping device. Also, while the survivor movement in the PDRN is modeled by different types of random walk, the current network assumes that survivor motion is modeled by the Levy walk.

The rest of the paper is organized as follows. Section 2 gives an overview of previous work related to mobility models that can be used to model survivor movement in search and rescue networks. Section 3 discusses our proposed solution. Section 4 discusses the simulation model of the scheme. Section 5 discusses the simulation results and concluding remarks are made in Section 6.

2. RELATED WORK

Mobility modeling is an important aspect of ad hoc network design. Different mobility models have been proposed for device mobility in these networks. A survey of these models is presented in [3] and the models include the random walk, the random waypoint [4, 5] and the Gauss-Markov model [6]. A random walk (RW) is a search algorithm that uses no topology information and the next hop is chosen uniformly among the neighbors of the node. Thus, RW is based on a random choice of direction and speed. Both the random waypoint and the Gauss-Markov model are different types of random walk. The two-dimensional RW model is used in the search and rescue process in [1, 2].

Levy walks have been applied to a diverse range of fields such as those that describe animal foraging patterns [7, 8, 9, 10], the distribution of human travel [11], the stock market [12], some aspects of earthquake behavior [13], anomalous diffusion in complex systems [14, 15, 16], epidemic spreading [17, 18] and human mobility [19].

3. PROPOSED SOLUTION

The purpose of this paper is to extend the work in [1] by studying the movement of survivors in the PDRN using the Levy walk models when barriers are present. Barriers are obstacles that prevent survivors and crewmembers from moving freely around a disaster area. We first provide a brief description of the PDRN.

In the PDRN, when disaster occurs, inexpensive devices are randomly dispersed over the disaster area by, for example, being dropped off from a helicopter. Also, access points are deployed at the periphery of the disaster area and they are designed to communicate with a Command Center that is also located outside the disaster area. When the device hits the ground, it uses a built-in GPS functionality to locate its coordinates. It then attempts to communicate with the Command Center via one or more access points to register its location coordinates and thereafter it begins to continuously emit a beeping sound that is designed to attract wandering survivors. Thus, because the exact location of a beeping device is known to the Command Center, once a survivor reaches any such device, his/her location is completely known at the Command Center from where a rescue team will be dispatched to rescue them. Also, it is assumed that once a survivor reaches a beeping phone and talks to the Command Center with the phone, the phone will stop beeping. The architecture of the network is shown in Figure 1.

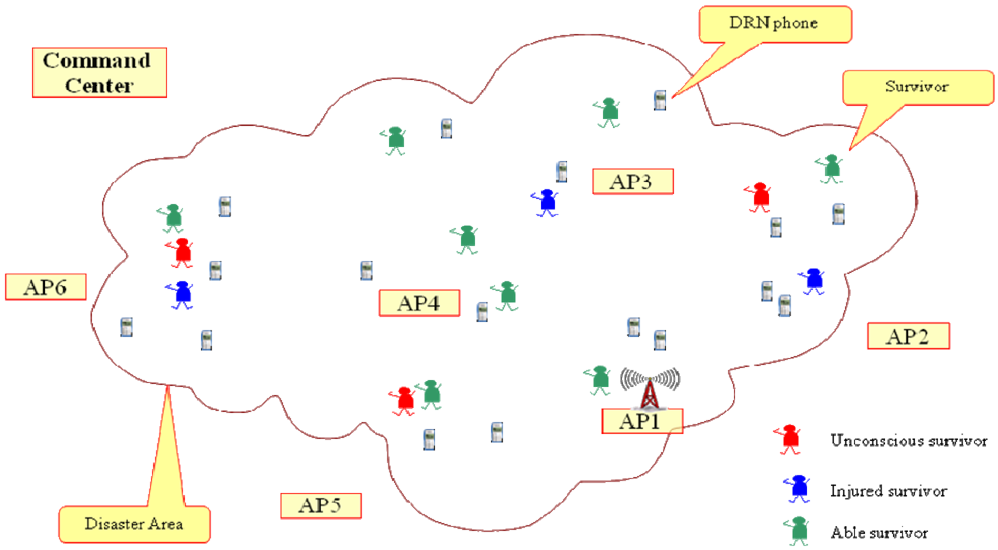

Figure 1: PDRN Architecture

3.1 PDRN with Barrier

The PDRN was designed for disaster areas where there are no barriers to survivors' movement. However, in real disaster areas survivor movement is usually hampered by debris and other barriers like fallen trees. Our solution assumes that barriers exist in the network with the result that some of the beeping devices are inaccessible because they are located in areas that survivors cannot reach. Thus, when a survivor reaches a barrier, he/she will change direction to avoid the barrier. The exclusion of barriers gives rescue teams a vague idea of the time needed to rescue survivors and limits their ability to plan for highly effective operations.

3.2 Mobility Models

The model used in [1, 2] discusses the movements of survivors in the PDRN using random walk models towards beeping phones. However, random walk models have the problem that random walkers tend to return to their starting points very often. Another type of walk used in search and rescue operation is the Levy walk.

One of the advantages of the Levy walk over the random walk is that the probability of a Levy walker returning to a previously visited site is smaller than in the random walk. Also, the number of sites visited by n random walkers is much larger in the Levy walk than in the random walk. The n Levy walkers diffuse so rapidly that the competition for target sites among themselves is greatly reduced compared to the competition encountered by n random walkers. The latter typically remain close to the origin (or their starting points) and hence close to each other [20, 21, 22, 23]. This dispersive feature of the Levy walk is advantageous in the PDRN network where factors such as the concentration of survivors and the distribution of phones are considered. Irrespective of survivors' locations each survivor's trajectory is likely to be different, and hence when competing to reach the dispersed phones, a Levy walk model ensures that the probability that two or more of them are heading for the same phone will be greatly reduced. Thus, with respect to the PDRN, the Levy walker will occasionally take long steps and thus is more likely to reach the vicinity of a beeping phone than a random walker.

3.3 Introduction to Levy Flight

A Levy flight is a mathematical description of a cluster of random short moves connected by infrequent longer ones. Thus, it consists of random walks interspersed by long travels to different regions of the walk space. Mathematically, the sequence of random movements of length *L* has a probability distribution function (PDF) $f_L(l)$ that obeys the power law; that is,

$$f_L(l) \propto l^{-\gamma}, \qquad 0 < \gamma \leq 3 \tag{1}$$

This PDF is said to have a heavy tail because large values of *L* are more prevalent than in other distributions such as Poisson and normal distributions. *L* has an infinite variance over the range of values of γ in equation (1). Typically, each flight is followed by a pause time whose duration also has a power-law distribution.

Because the mean length of a Levy flight is infinite, it is customary to use the *truncated Levy flight* in performance studies. The truncated Levy flight, which has a finite mean, can be defined as follows. Let $f_L(l)$ be the PDF of the length of flights in a Levy flight. The PDF of the length of flights in a truncated Levy flight is given by

$$f_Y(y) = \begin{cases} cf_L(y) & -y_0 \leq y \leq y_0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where c is a normalizing constant and y_0 is the cutoff flight length. Thus, in a truncated Levy flight, the length of each flight cannot exceed a pre-defined threshold value, which is y_0.
As discussed earlier, Levy flights have been applied to a diverse range of fields such as those that describe animal foraging patterns, the distribution of human travel, the stock market, earthquake behavior, anomalous diffusion in complex systems, epidemic spreading and human mobility.

3.4 Levy Walk versus Levy Flight

The difference between a Levy walk and a Levy flight lies in the velocity. In a Levy flight, the walker visits only the endpoints of a walk length and the notion of velocity does not come up and each walk takes zero time to complete. This means that in a Levy flight, the walker is only either at the end of the a walk length (or jump) or at the beginning; there is no stop in between the jump. However, in a Levy walk, the walker follows a continuous trajectory from the beginning of the walk to the end and this leads to a finite time being needed to complete the walk. In this paper we deal with the Levy walk because one of our performance measures is the mean time to rescue a survivor.

Because we are conducting a performance study, we will use the *truncated Levy walk* instead of the traditional Levy walk. A truncated Levy walk is to the Levy walk what the truncated Levy flight is to the traditional Levy flight.

3.5 Levy Walk Models of Survivor Movement in PDRN

In the PDRN a walker (or survivor) starts out walking aimlessly (or in a random manner) until he/she reaches the vicinity of a *beeping zone*. A beeping zone is an area within which a survivor hears the beeping of a phone. Since the Levy walk is a pure jump process, it is more likely to “leap” over a beeping phone. This means that when a Levy walk is used, the value of the next step is likely to fall beyond a point where a phone is located than at that position. Thus, even though the Levy walker takes short steps most of the time, the few longer steps are likely to result in his leaping over of a beeping zone. This means that a walk is not likely to terminate at the phone. For this reason, we use a hybrid model that utilizes the Levy walk until a survivor comes in the vicinity of a beeping zone where he switches over to a form of random motion we call the rewarded (or reward-based) random motion. The phones that are dropped in disaster area are at random discrete locations. When a Levy walk is performed it will be impossible for the walker to reach the exact location of a phone. In fact, it is known that the PDF of the first passage time of a Levy flight follows the form $f_T(t) \propto t^{-3/2}$, which implies that mean first passage time is infinite [24]. Therefore a termination condition is set to the point where the distance between the phone and the survivor is less than 0.5 meters, which is the beeping radius in our simulation model.

3.6 Reward-Based Random Motion

The results in [1, 2] indicate that the performance of the system is greatly enhanced if a reward-based random motion is practiced inside a beeping zone. A reward-based walk (or a rewarded walk) is one in which a deliberate attempt is made by the walker to avoid going in directions that lead to a decrease in the volume of the sound of the beeping phone. Thus, in a classical walk the walker is walking aimlessly while in a rewarded walk, he/she is attempting to walk purposely toward a beeping phone. In our work we assume that a rewarded random walk is used in the beeping zone. This rewarded walk can be a rewarded Levy walk or a rewarded random walk. In both cases, the measure of the reward is an increase in the loudness of the sound from the beeping device. Thus, once the walker is within a beeping zone, he/she will use a restricted walk that favors movement toward the direction of the beeping device and away from a direction that causes a decrease in the loudness of the sound from the beeping phone.

3.7 PDRN with Barriers

As stated earlier, in [1] it is assumed that there are no barriers in the disaster area and as a result the survivors are free to move about anywhere in the area. In a more realistic environment the survivor movement and that of the crewmembers is hampered by the presence of obstacles, such as fallen trees and debris. In this paper we assume that there are barriers in the disaster area. When a walker encounters a barrier then in the next step the direction is selected from any valid direction that points away from the barrier. Thus, for the Levy walk this implies that the direction is uniformly distributed within the 180 degrees in front of the barrier.

4. SIMULATION MODELS

The analysis of the Levy walk is generally very complicated, which makes simulation the preferred method of analysis. It is assumed that the predefined threshold flight length of a truncated Levy walk is 0.75m, and the length of a random walk is fixed at 0.5m. At the end of each step, the survivor does not wait at that location if there is no beeping phone available. Thus, the pause time is zero. Initially the walker can uniformly choose any direction within the unit circle. The velocity of a Levy walk is assumed to be 1 m/second. When he/she encounters an obstacle, the direction will be uniformly distributed within a semicircular arc subtended by the obstacle.

4.1 Barrier Model

The barrier as a simulation parameter is assumed to be uniformly distributed in airspace. It is assumed that there are ten barriers within the disaster area with each barrier having a length of 6m. The barriers are assumed to be reflecting as a survivor is not expected to stop walking in a disaster area without communicating with the Command Center. During the reward-based walk, it is assumed that when a survivor reaches a barrier, he/she is equally likely to turn either left or right in search of a different route and continues walking in search of a beeping phone or to continue his walk outside a beeping zone, if the rewarded random walk is used. For rewarded Levy walk, the survivor chooses a direction within the 180 degrees profile defined by the front of the obstacle.

4.2 Levy Walk Models

The Levy walk models considered are as follows:

- Levy walk to Levy walk (LEVY_LEVY), which means that the walker uses the Levy both outside and inside a beeping zone. Thus, he/she does not take advantage of a beeping zone to narrow the search
- Levy walk to rewarded Levy walk (LEVY_RLEVY), which means that the walker starts with the Levy walk and when he/she reaches a beeping zone the next direction for the Levy walk is one that goes in a direction with increased beeping sound.
- Levy walk to symmetric random walk (LEVY_SRW), which means that the walker starts with the levy walk and when he reaches a beeping zone he/she switches to an unrewarded symmetric random walk.
- Levy walk to rewarded symmetric random walk (LEVY_RSRW), which means that the walker starts with a Levy walk and when he/she reaches a beeping zone, he/she switches to the rewarded symmetric random walk.

As a point of comparison, we also consider results for symmetric random walk to symmetric random walk (SRW_SRW) in which the walker uses the symmetric random walk both outside and inside a beeping zone, and the symmetric random walk to rewarded symmetric random walk (SRW_RSRW) in which the walker starts with the symmetric random walk and switches to the rewarded symmetric random walk inside a beeping zone. These two models are used in [1, 2].

4.3 Survivor and Phone Distributions

Different configurations of survivor and phone distributions can also considered and these include:

a) Survivors and phones are uniformly distributed
b) Survivors and phones are normally distributed
c) Survivors are uniformly distributed and phones are normally distributed
d) Survivors are normally distributed and phones are uniformly distributed

The results in [1] indicate that a mixed distribution strategy does not perform as well as a homogeneous distribution strategy. Therefore, in the remainder of the paper we limit the discussion to schemes (a) and (b).

The configurations also cover the case when the number of phones is fixed and the number of survivors is varied, and the case when the number of survivors is fixed and the number of phones is varied. The reason for this configuration is to understand how dropping a fixed number of phones in a disaster area regardless of not knowing how many survivors are in the area affects the efficiency of rescuing survivors, and also how dropping as many phones as possible in a disaster area when there is a knowledge of how many survivors are in the area affects the efficiency of rescuing survivors.

5. SIMULATION RESULTS

The simulations were run on MATLAB software. The area studied is assumed to a 1 km by 1 km dimension. The parameters of interest are the mean first passage time (MFPT) and the percentage of survivors who reach a beeping phone and are rescued. MFPT is the mean time it takes for a survivor to reach a beeping phone from the beginning of the search process. The battery life of the phones affects the simulation results and is varied from 2 hours to 8 hours.

Figures 2 through 9 show the results that were obtained from the various simulations that were run. From the graphs it can be seen that the worst performance is obtained when a survivor does not switch to a rewarded walk within the beeping zone. The reason for this is because when a walker does not switch to a rewarded walk type within a beeping zone, he/she essentially continues to walk aimlessly all the time, which leads to the poor performance. For this reason, the worst performance is obtained in the LEVY_LEVY and LEVY_SRW models. The SRW_SRW model performs slightly better, but the performance is still not as good as that of any scheme that switches to a rewarded walk within a beeping zone. Finally, all the schemes that switch to a rewarded walk within a beeping zone tend to behave equally well. Their MFPTs are approximately half that of SRW_SRW and approximately one quarter of those of the LEVY_LEVY and LEVY_SRW.

The percentage of survivors rescued under the LEVY_LEVY and LEVY_SRW models is almost zero. The highest percentage of customers rescued is obtained in the rewarded models. While this is dependent on the number of phones dispersed in the disaster area and the battery life, it ranges from 30% to close to 90%.

The distribution of the survivors and phones also affects both the MFPT and the percentage of survivors rescued. The better results are obtained when the survivors and phones and normally distributed when compared to the both of them being uniformly distributed.

The battery life of the phones has an impact on the number of survivors that will be rescued in a given area. This is because as the battery life increases, the number of rescued survivors increases. Also, as the battery life increases, the MFPT first decreases and later remains constant with little decrease.

Finally, when the number of survivors is fixed, the performance of the system improves as the number of phones deployed in the area increases. This is because by increasing the density of the phones in the area the average distance that a survivor traverses before reaching a phone becomes smaller and the mean first passage time decreases. Similarly, when the number of phones deployed in area is fixed, the performance of the system becomes worse as the number of survivors increases. This is because as the number of survivors increases, the fraction getting to a beeping phone becomes smaller, which causes the mean first passage time to increase. Note that these results are based on the assumption that a phone can only be retrieved by one survivor.
In [25] it is shown that the results obtained for a 3km by 3km disaster area exhibit the same behavior as those obtained for a 1km by 1km disaster area.

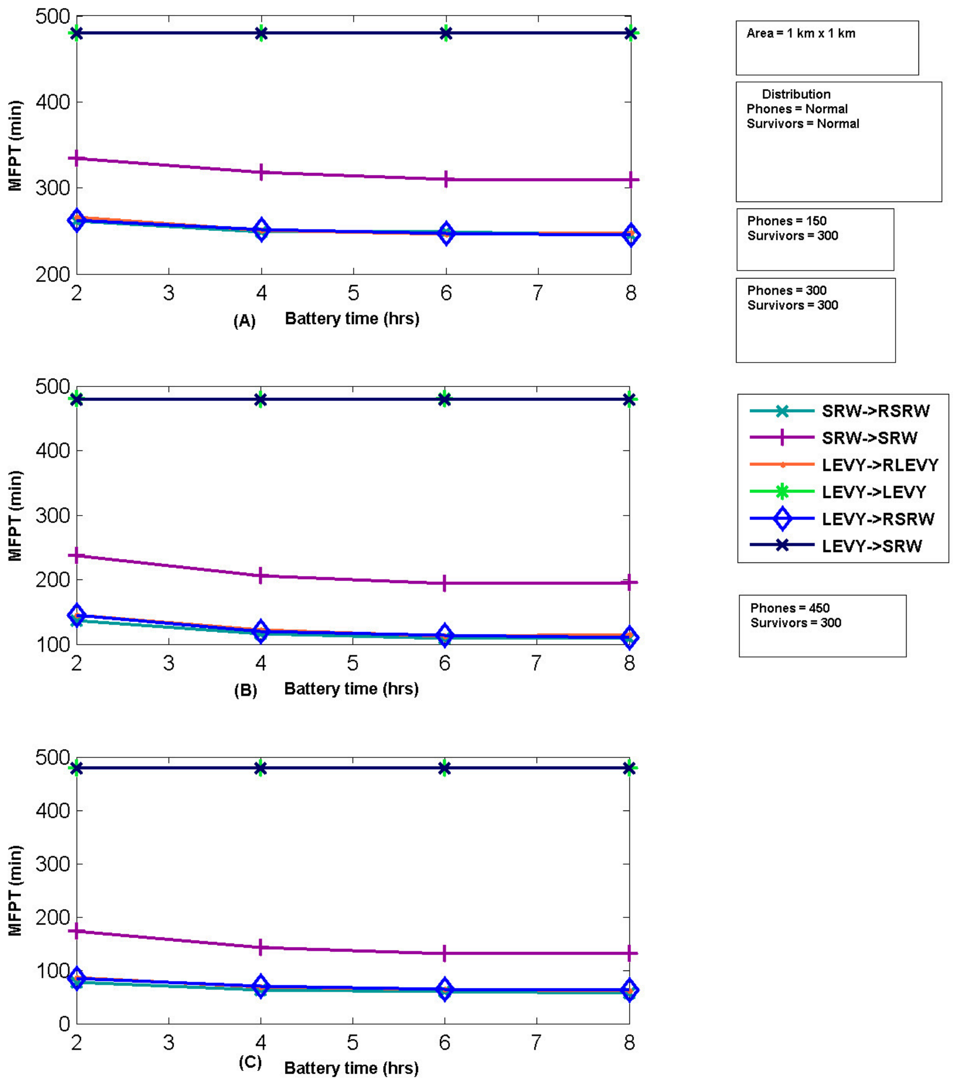

Figure 2: MFPT of survivors reaching a target when the Area is 1km by 1km, with both Phones and Survivors normally distributed and a constant number of Survivors

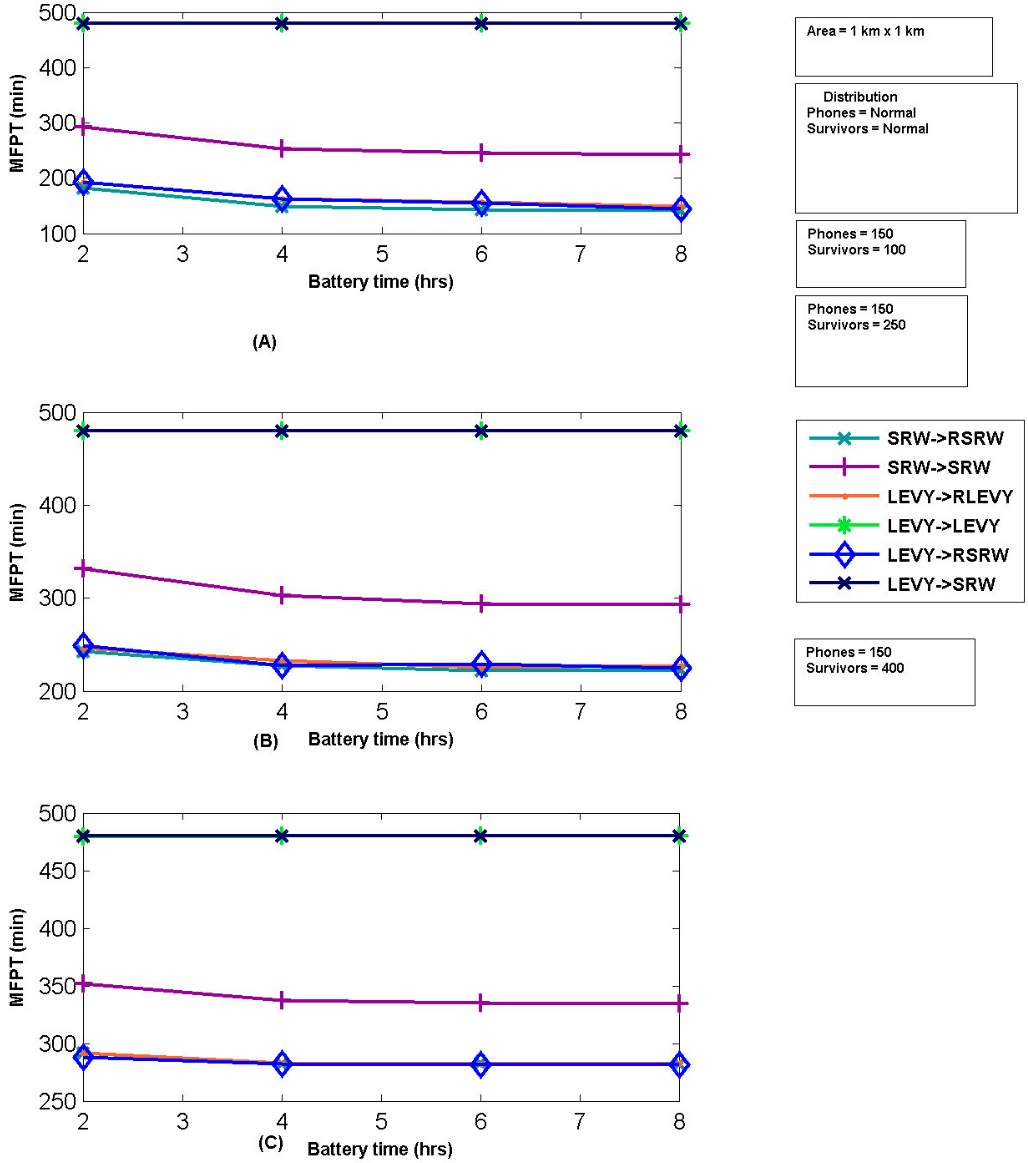

Figure 3: MFPT of survivors reaching a target when the Area is 1km by 1km, with both Phones and Survivors normally distributed and a constant number of Phones

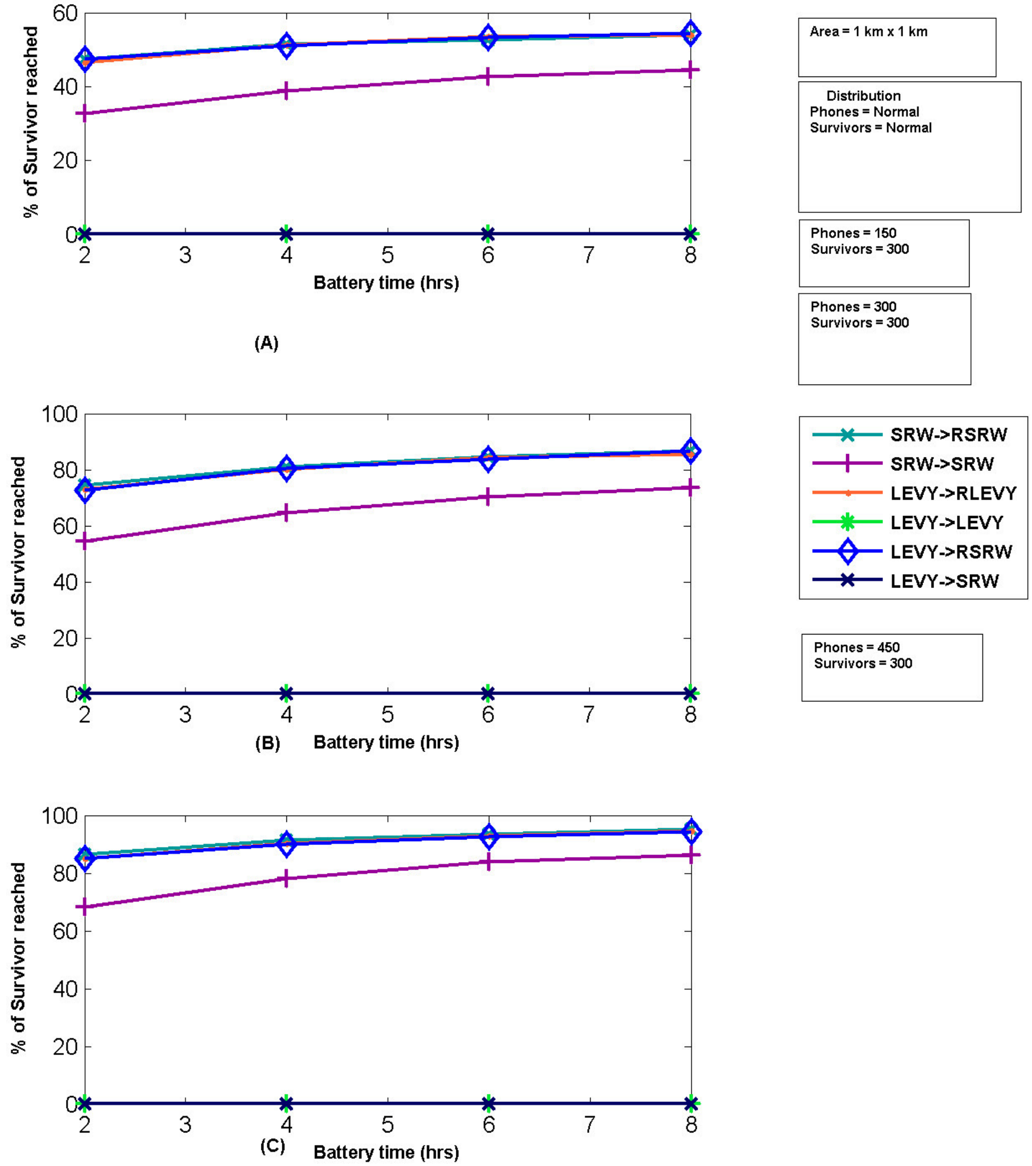

Figure 4: Percentage of Survivors reaching a target when the Area is 1km by 1km with both Phones and Survivors normally distributed and a constant number of Survivors

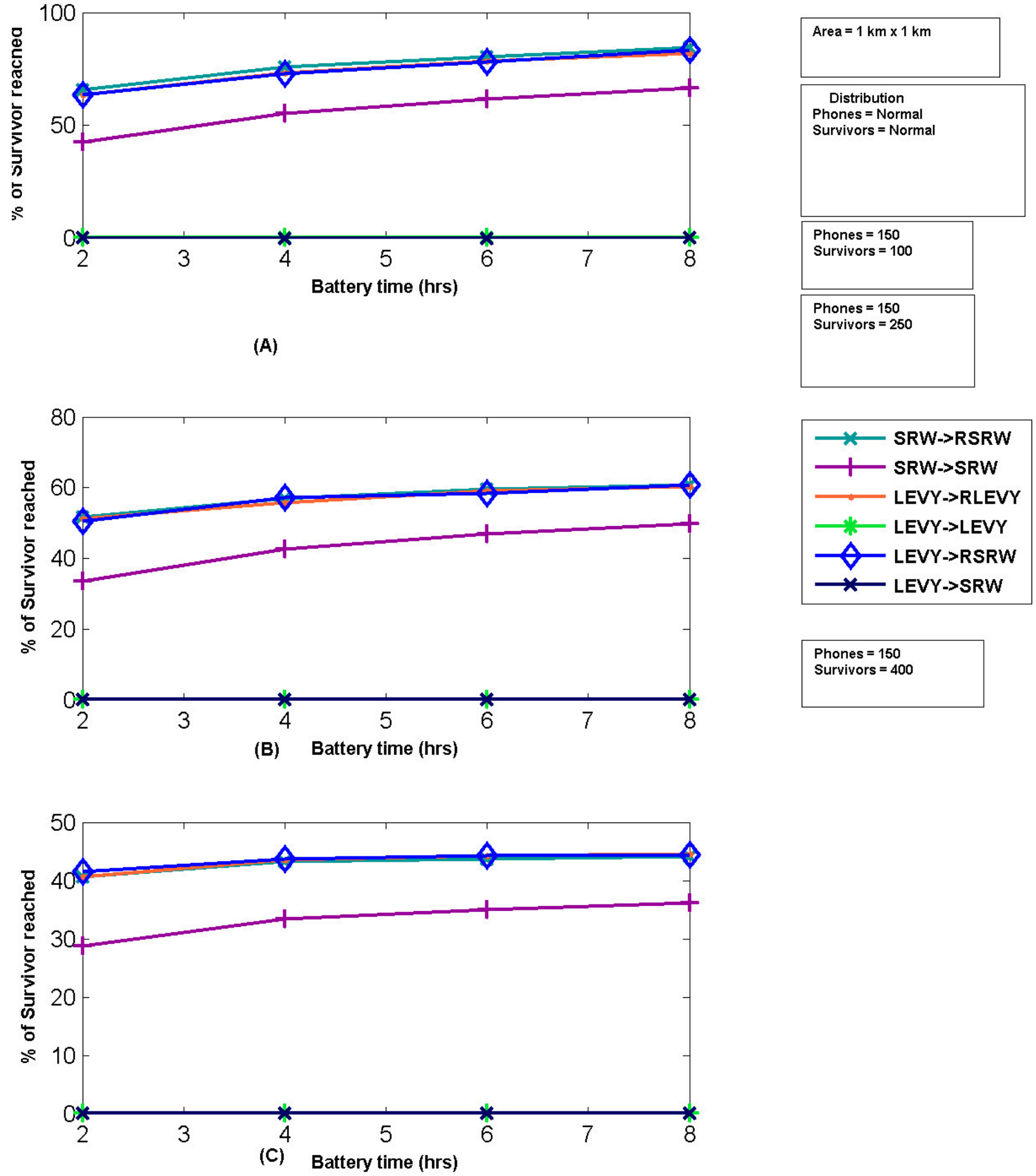

Figure 5: Percentage of Survivors reaching a target when the Area is 1km by 1km with both Phones and Survivors normally distributed and a constant number of Phones

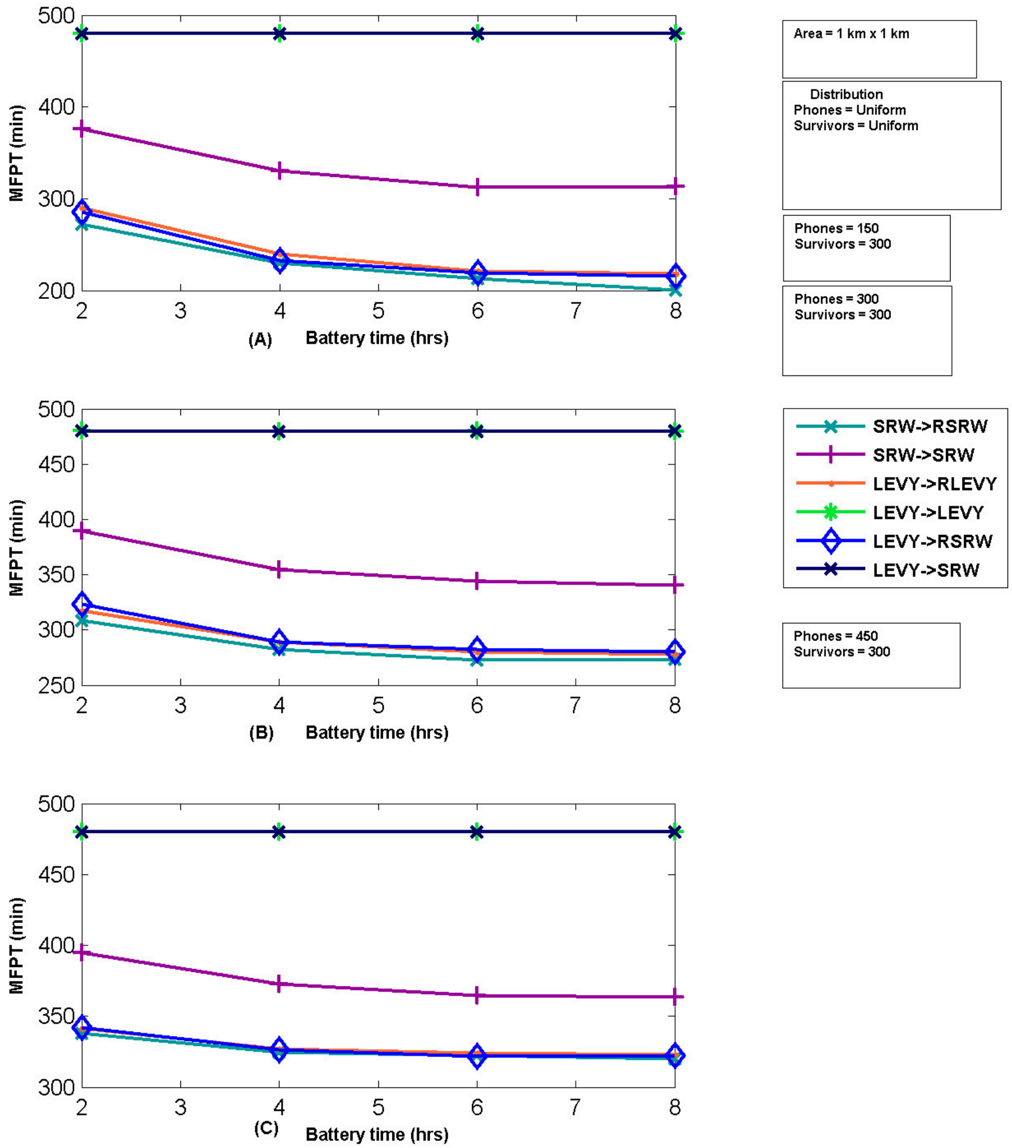

Figure 6: MFPT of survivors reaching a target when the Area is 1km by 1km, with both Phones and Survivors uniformly distributed and a constant number of Survivors

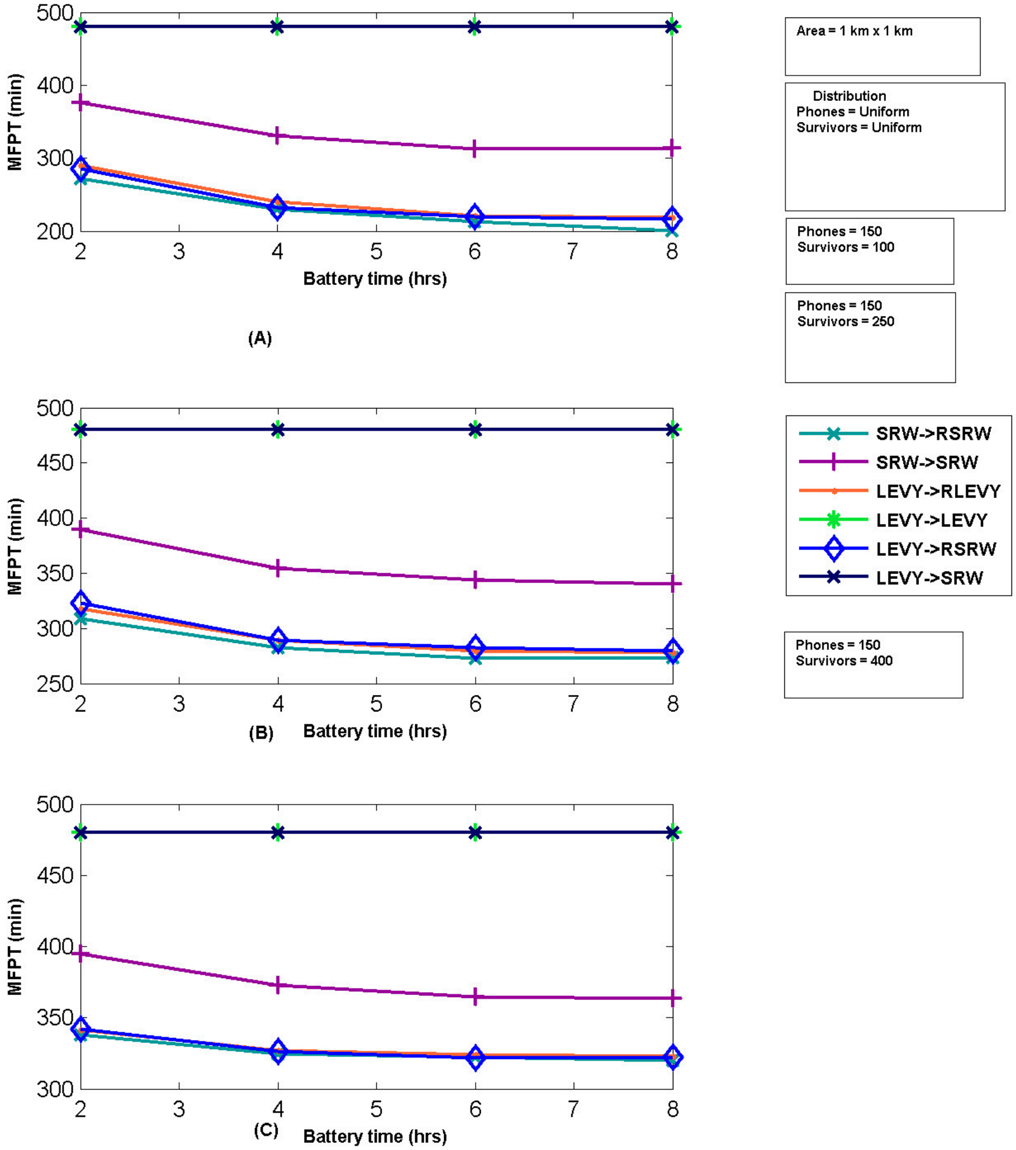

Figure 7: MFPT of survivors reaching a target when the Area is 1km by 1km, with both Phones and Survivors uniformly distributed and a constant number of Phones

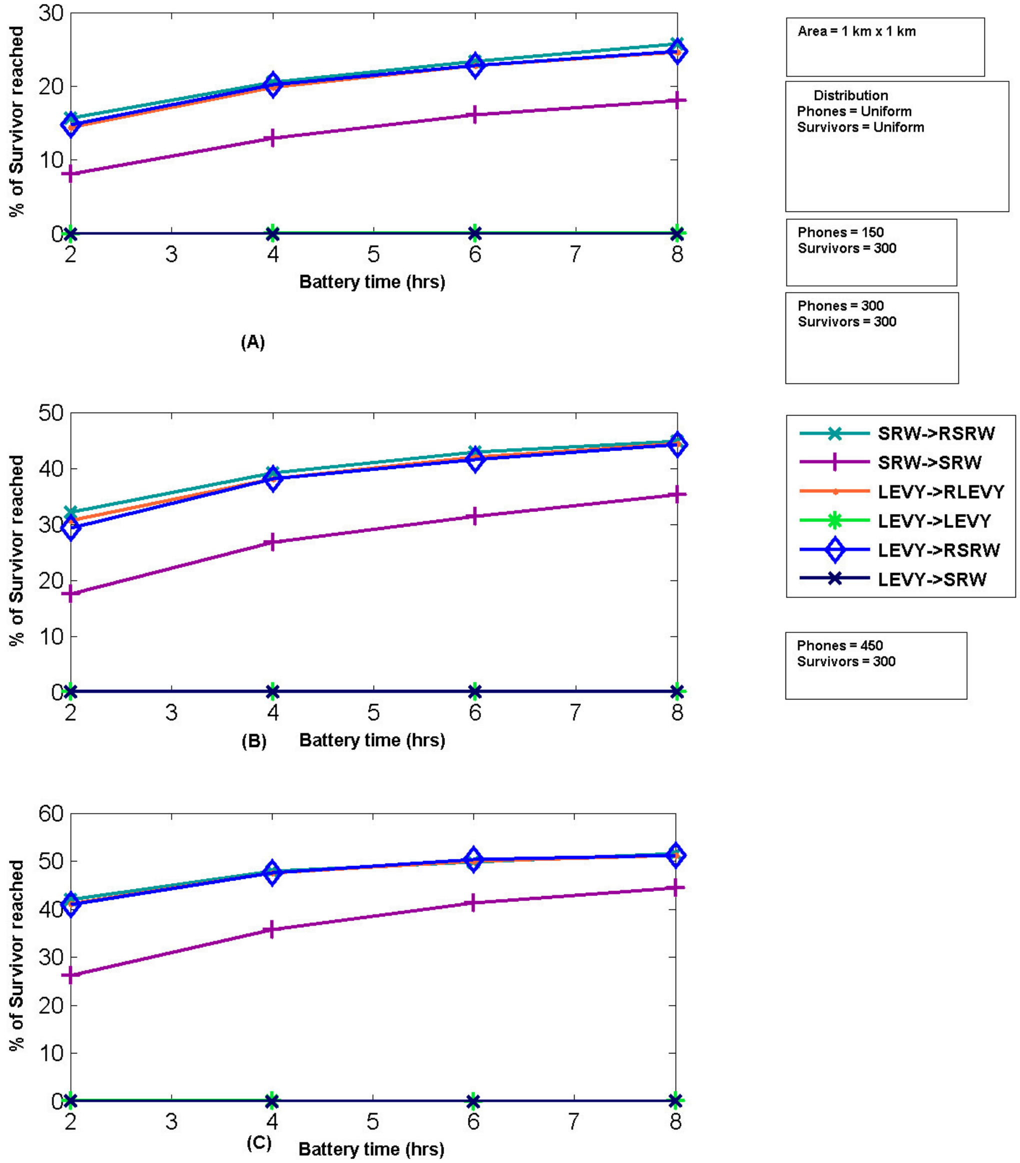

Figure 8: Percentage of Survivors reaching a target when the Area is 1km by 1km with both Phones and Survivors uniformly distributed and a constant number of Survivors

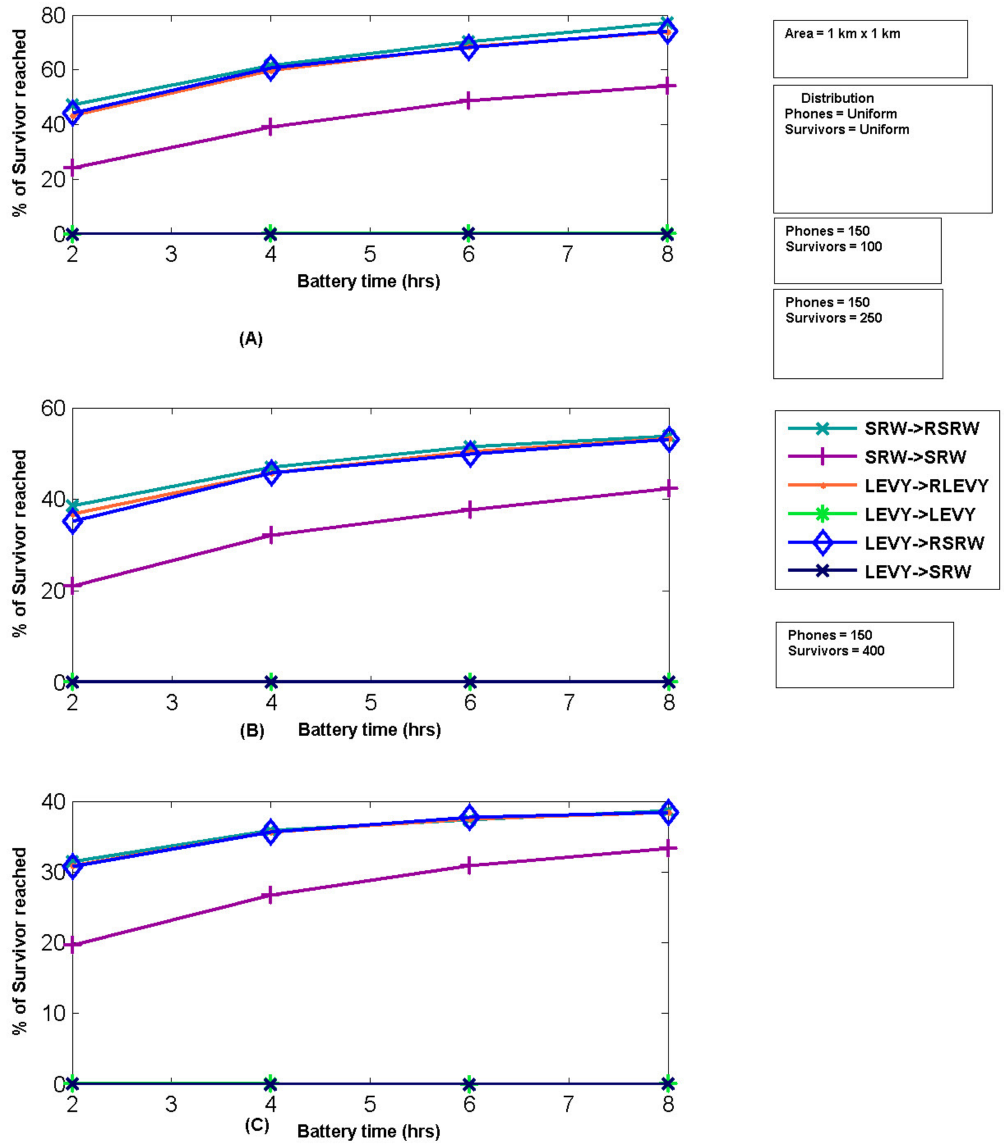

Figure 9: Percentage of Survivors reaching a target when the Area is 1km by 1km with both Phones and Survivors uniformly distributed and a constant number of Phones

6. CONCLUSION

In this paper, we have proposed different Levy walk and random walk models that show the movement of survivors in the Portable Disaster Recovery Network with barriers. The Portable Disaster Recovery Network is a communication infrastructure that enables survivors to communicate with rescue crewmembers to enable them to be rescued quickly. The rescue devices are dropped in a disaster area from helicopters and start beeping immediately they reach the ground. While the movement of survivors in a disaster area when modeled by Levy walk is faster than that of random walk because of the continuous jumps assumed to be made by the survivors, with Levy the survivors have a tendency to leap over the phones without seeing them hence. This limitation is addressed by defining a reward-based model that requires the survivor to switch from the Levy walk to a random walk within a beeping zone such that the movement within a beeping zone is biased in favor of directions with louder beeps.

The performance measures of the model considered include the mean first passage time, which is the average time it takes a survivor to reach a phone, and the percentage of survivors that reach a phone and are, therefore, rescued. It can be observed that the distribution of survivors and the phones in the disaster area has an impact on the two performance measures mentioned. The best results are obtained when both the survivors and phones are normally distributed followed by when both are uniformly distributed. The results indicate that when the number of survivors is fixed, the performance improves as the number of phones being dropped increases. If the number of phones is fixed in a given area, the percentage of survivors rescued will decrease as the number of survivors in the disaster area increases. This is because as the phones remain constant, the survivors in the area start to increase and not enough phones are available for the survivors to use. Finally, the percentage of survivors rescued increases as the battery life increases.

The results shown are of a 1 km by 1 km area and the conclusions do not change when a 3 km by 3 km area is studied [25].

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