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Research Article

The Performance Assessment of a MANET using WUGF

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Abstract: The emphasis in this study is on executing the MANET reliability using Weighted Universal Generating Function (WUGF). MANET is a self-configuring network connected by wireless links. The performance evaluation of a MANET is the probability of transferring the message successfully from the source to the destination without any delay. This study is devoted to assess the MANET reliability in a Universal Generating Function (UGF) paradigm. By introducing different composition operators over UGF, the physical happening of the network can be predicted. The computation procedure will become cumbersome if the number of nodes in the network increases. Hence this study introduces a novelty approach-WUGF to achieve the reliability of a MANET. A novelty algorithm has been designed to assess the reliability using WUGFT and is validated with a case study in the military test bed.

Keywords: Group communication application, MANET, multicasting, network reliability, universal generating function, weighted universal generating function

INTRODUCTION

The exemplar of wireless Mobile Ad hoc Networks (MANETs) is becoming more popular because the mobile devices are getting more and more pervasive. Most of its employment is confined to the military arena up. Now a day, wireless ad-hoc networks are one of the most important field of communication and networks. A MANET is a self-configuring network of mobile routers connected by wireless links. It can be easily deployed in a short time and users can access and manipulate data anytime and anywhere. The nodes are always moving freely, enter and leave the network at any time.

MANETs due to their quick and economically less demanding deployment find applications in several areas like military application, collaborative and distributed computing and emergency operations. Reliable and quick communication is of prime importance for these fields. They also require the support of reliable and secure multicasting. For example, the leader of a group of soldiers may want to give an order to all the soldiers or to a set of selected personnel involve in the operation. MANET provides the required communication quickly. Group communication plays a major role in developing distributed mobile application. Multicast (MC) is an efficient method for achieving group communications. It can improve the efficiency of the wireless links. Hence it is envisioned for group-oriented computing, especially, when the members are dynamic. MC plays a vital role in the domains like military battlefields, emergency situations, classrooms and conventions where members are sharing information dynamically using their mobile devices. A MC can reduce communication costs and the delivery delay (Siva Ram Murthy and Manoj, 2011).

Reliability engineering is the discipline of ensuring that a system will be reliable when operated in a specified manner. Network reliability is an important part of planning, designing and controlling network. Designing, developing and testing real applications for ad hoc network environments still deserves particular attention by the MANET research community. Such networks find applicability in military environments, where a platoon of soldiers of fleet of ships may construct an ad hoc network in the region of their deployment. This has necessitated the development of innovative MANET solutions catering to the reliability of the defense communications environment. They represent a great incentive for mobile users to adopt the MANET technology in the daily life. In such applications, the used ad hoc networks need to be reliable and secure.

The reliability analysis of various networks becomes a major concern for several decades. There are many approaches for executing network reliability (Levitin, 2001; Yadav *et al*., 2008; Lei *et al*., 2010). Chaturvedi and Misra (2002) have proposed a hybrid method to evaluate the reliability of complex networks.

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Du *et al*. (2014) have analyzed the reliability of a single-unit system with multi-physical mission. Yeh (2008a), Yeh and Yeh (2011) and Meena and Vasanthi (2012) have evaluated the reliability of a stochastic flow network in terms of minimal paths. Yeh and Yeh (2011) have calculated the multi-state flow network reliability based on path set.

In a Multistate System (MSS), both the system and its components are allowed to experience more than two possible states, e.g., completely working, partially working, or partially failed and completely failed. MIN is a generalization of the tree-structured Multistate System (MSS). It has a source node, a number of sink nodes and a number of intermediate nodes. The source node can only emit and transmit the message to other nodes and the number of sink nodes will only receive the messages. The intermediate nodes will retransmit the received message to some other non-source nodes. The traffic will be carried out in the network from a non-sink node to a number of non-source nodes through the edges between the nodes.

Different approaches are there to assess the reliability of MIN (Yeh, 2008b; Yeh and He, 2010). Among these approaches, the UGFT outperforms other related methods. UGFT presents several advantages over the other existing methods in reliability calculation. The first UGFT was proposed by Ushakov (1986). This approach is intuitive simple recursive procedures combined with simplified techniques. This technique was introduced by Levitin (2013) for an Acyclic Multi Information Networks (AMIN). It was improved by Yeh (2006) applying some simplified techniques. Malinowski and Preuss (1996), Lisnianski and Levitin (2003) and Levitin (2005) have evaluated the reliability of different types of AMIN using UGFT. Yeh (2008a) applied an extension to UGFM to search the entire one-to-many d-MP of Acyclic multi state-arc-flow conservation networks. Also Yeh (2009) executed an algorithm using UGFM for finding all MP in a Binary State Network (BSN). Meena and Vasanthi (2013, 2014) have evaluated the MANET reliability using UGF under CHGR protocol.

G. Levition used UGF for multi-state vector k-out-of-n system model. Ding *et al*. (2008) introduced Fuzzy UGF for obtaining the performance evaluation of a Multi-state weighted-k-out-of-n systems. Eryilmaz (2013) has executed the reliability of a k-out-of n system by considering random weights. Due to their stochastic nature, MANETs are having multi state capacities that are in working or in non-working or in partial working. MANET reliability can be obtained by considering all the possibility of passing the information between the nodes and finally reaches the target. The possibilities will grow exponentially if the number of nodes increases. The introduction of random weights based on the flow of information, will reduce the computational complexity. So far UGFT is used for reliability calculation of MIN, MSS, MANET, BSN and ABSN. The main purpose of this study is by introducing random weights based on the transition step and obtains the MANET reliability by applying Weighted Universal Generating Function Technique (WUGFT).

MATERIALS AND METHODS

UGF allows one to evaluate an output performance distribution for a wide range of systems characterized by different topology, different natures of interaction among system elements and the different physical nature of elements performance measures. UGF plays an important role in finding out the expected capacity for each traffic-path involved in the MANET and also in the evaluation of system reliability. Then the UGFT approach is based on the definition of a u-function of multistate elements, which are of discrete random variables and composition operators over u-functions.

There are two types of UGFs in the existing design. One is for individual node which is also called as node UGF (defined for source and neighboring nodes). It forms the basic elements for the UGF and the other is the Path Universal Generating Function (PUGF) formed by the composition of individual UGF with the source where it receives information. The existing algorithm to evaluate the performance of a MANET using UGFT is as follows:

Step 1: Define the UGF for each sub source (source) of the available sub MANETs:

$$U\,(S) = \sum_{N \subseteq \theta_n} P_{n:N} X^N$$

Step 2: Define the UGF for all neighboring nodes except the sub source in each sub groups:

$$U\,(n) = \sum_{N \subseteq \theta_N} P_{n:N,T} X^T$$

Step 3: Composite the path UGF U (n) as a polynomial in X as U (n) = u (S) ⊗ u (n).

Step 4: Compute the reliability of sub MANETs using rule 7.

Step 5: Calculate the reliability of MANET using rule 8.

It can be argued that in the existing UGFT design, the number of u-functions increase as the number of nodes and possibilities increases. There are n (2^{n-1} + 2) u-functions for each participating nodes. This will result in a crucial factor of computation for the exact performance evaluation. This novelty design reduces the length of u-functions by introducing using random weights and makes the commutation facile.

Novelty weighted UGF design: Figure 1 outlines a simple MANET with a source and 3 members. Node 2 is treated as the source and the nodes 3, 4 and 5 are

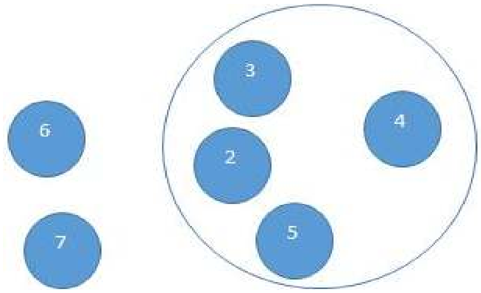


Fig. 1: A simple MANET

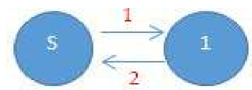
participating nodes whereas the nodes 6 and 7 are the non-participating nodes all the four nodes in the group can communicate with each other. Based on the requirement, the source node 2 may pass the information to the nodes 3 or 4 or 5 or {3, 4} (two nodes at a time) or {3, 5} or {4, 5} or {3, 4, 5}. The member nodes will clarify the queries received from source and send it back to node 2. Hence node 2 plays the role of both source and destination. The member nodes will receive same kind of information a maximum of two times only.

Weighted UGF: Weighted Universal Generating Function (UGF) is introduced in this study so as to reduce the computational complexity. For example, suppose the MANET has n nodes including source node then the possibility of exchanging information between the nodes will grow exponentially n ($2^{n-1} + 2$). This will make computation process a crucial one. Hence the WUGF is introduced to reduce the time complexity. That is for each PUGF, the step sizes are identified and based on it, random weights are allotted. Hence PUGF becomes WPUGF. The SM reliability includes all the possibility of passing information initiated from the sub source through its member nodes and reaches the sub source again. Any information may reach the sub source directly at a maximum of 2 steps. If 2 steps clarification is not sufficient then the information is passed to the other nodes and finally reaches the sub source either directly (or) in 3 steps (or) in 4 steps (or) in n steps. Based on this weights 2 (or) 3 (or) ….(n) will be allotted so as to reduce the length of u-function in the path UGF.

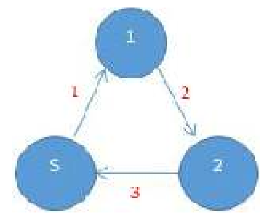
Figure 2 explains how the message is transmitted in 2, 3 and 4 steps within the MANET. The successful transformation needs two steps in the first one, takes 3 steps in the second one and needs 4 steps in the last two. Figure 2a shows that the successful transition needs two steps where as in Fig. 2b, it takes 3 steps. Figure 2c and d the clarity of information is achieved in four steps.

Definition 1: The Individual UGF-u (S) for the source (sub source) is defined as a polynomial in X as:

$$u(S) = \sum_{N \subseteq \theta_S} P_{S:N} X^N$$



(a)



(b)

(c)

(d)

Fig. 2: Example message transmission in 2, 3 and 4 steps with in MANET given in Fig. 1

where, $P_{S:N}$ is the probability that the set of nodes $N \subseteq \theta_S$ receiving information directly from source node S. Here θ_S denotes the non empty set of elements form a node sub set that are directly reachable from node i. e.g., In Fig. 1 $\theta_2 = \{3, 4, 5\}$.

For Example, in Fig. 1, the individual UGF for the source node 2 is given by:

$$u(2) = P_{2:3}x^3 + P_{2:4}X^4 + P_{2:5}X^5 + P_{2:\{3,4\}}X^{\{3,4\}} + P_{2:\{3,5\}}X^{\{3,5\}} + P_{2:\{4,5\}}X^{\{4,5\}} + P_{2:\{3,4,5\}}X^{\{3,4,5\}}$$

Definition 2: The weighted individual UGF-u (n_w) for neighboring nodes is defined as a polynomial function of X by:

$$u(n_w) = \sum_i n_i P_{n:N,D} X^D \; N \subseteq \theta_N$$

where, $P_{n:N,D}$ is the probability that the set of nodes $N \subseteq \theta_N$ receiving information directly from node n and transmits it within the group (only one time repetition is permitted) and finally reaches the destination D. Here n_i represents the step size that the information initiated from node n is reached D in i steps. The inclusion of n_i will make the reliability calculation easier.

For Example, in Fig. 1, individual UGF for the neighboring node 3 is given by:

$$u(3) = [P_{3:2} + P_{3:4,2} + P_{3:5,2} + P_{3:4,3,2} + P_{3:4,5,2} + P_{3:5,4,2} + P_{3:5,3,2} + P_{3:\{4,5\}::\{\varphi,2\}} + P_{3:\{4,5\}::\{2,\ \varphi\}} + P_{3:\{4,5\}::\{2,2\}}]\ X^2$$

Here the information started form node 3 will reach the node 2 in one step. It needs 2 steps for the information to reach D that is sent to nodes 4 or 5 from 3. For the remaining possibilities it takes 3 steps to reach D. Hence in this case n = 3, D = 2 and i = 1, 2 and 3. In the first term of u (3), the message reaches 2 in one step (weight 1). From 3rd to 5th terms, it takes two steps (weight 2) and the remaining terms have three steps (weight 3) to reach 2. After applying weights u (3) can be modified as:

$$u(3) = \{[3_1 P_{3:2} + 3_2 [P_{3:4,2} + P_{3:5,2}] + 3_3 [P_{3:4,3,2} + P_{3:4,5,2} + P_{3:5,4,2} + P_{3:\{4,5\}::\{\varphi,2\}} + P_{3:\{4,5\}::\{2,\ \varphi\}} + P_{3:\{4,5\}::\{2,2\}} + P_{3:\{5,3,2\}}]\}\ X^2$$

Definition 3: The weighted path UGF-U (n_w) is defined using the node UGF and the composition operator-$\otimes$ as U (n_w) = U (S) $\otimes$u (n), n = 1, 2, 3,….., t, t = |N - D|. U (n) can be also defined as a polynomial function of X. U (n) = $\sum_i n_i P_{S:n,N::D}$ X^D. Here N and D represent the set of nodes and the destination respectively.

Key features of the proposed UGFT and reliability calculation: The following statements discuss some important key features of the proposed UGF.

Rule 1: Each transmission has its own state probability. Hence each transmission requires a unique representation. The probability of transmission of messages from i to the neighboring nodes j, k, l, … and reaching the terminal node D is denoted by $P_{i:j,k,\ldots D}\,X^D$.

For Example, from Fig. 1, the information received at 3 from source 2 may be passed to 4. From 4 it may be passed to 5 and it reaches the terminal node. This can be represented as $P_{2:3,\ 4,\ 5,\ 2}X^2$. The notation i: {j, k, l} refers that the information is passed from node i to nodes j, k and l simultaneously.

Due to mobility, sometimes the nodes cannot pass the received information to the neighboring nodes. This will lead to the conclusion that the message is terminated at that node and is represented by $P_{i:j,\varphi}X^{\varphi}$. Sometimes the information may be passed from i to more than one nodes simultaneously. Among these nodes, some of them may pass the messages to D or to neighboring nodes and some of them may not due to mobility. This kind of situation is represented by $P_{i:\{j,k\}::\{\varphi,D\}}\ X^{\{\varphi,D\}}$ or $P_{i:\{j,k,l\}::\{\varphi,D,D\}}\ X^{\{\varphi,D,D\}}$. In the first case, message is passed from i to j and k at a time and only the message received at k reaches the terminal and at j, the information is terminated. In the latter case, message is passed from i to j, k and l simultaneously and only the message received at k and l reaches the terminal and at j, it is terminated.

Rule 2: The inclusion of State Dependent Probability (SDP) like $P_{i:\varphi}$ plays a prominent role in identifying the working states. Here $P_{i:\varphi}$ denotes that the information is terminated at node i. The number of possible working states in the path UGF increases rapidly and making the computation tedious and time consuming. Hence by introducing state dependent probability, we can reduce the number of non-working states and include all the possible working states in UGF.

Rule 3: When the information or message is terminated at any node n, then the corresponding probability cannot be considered for calculating the reliability.

In Fig. 1, $P_{3:2}X^2 + P_{3:4,\varphi}\,X^{\varphi} + P_{3:4,5,2}\,X^2 + P_{3:5\varphi}\,X^{\varphi}$, the terms $P_{3:4,\ \varphi}\,X^{\varphi} + P_{3:5,\varphi}\,X^{\varphi}$ cannot be considered.

Rule 4: Using SDP, the following statements are valid:

$$P_{s:i,\{j,\ k\}::\{\ \varphi,D\}}X^{\{\varphi,D\}} = P_{s:i,k::D}\,X^D$$

For example, in Fig. 1:

$$P_{2:3,\{4,5\}::\{\varphi,2\}}\,X^{\{\ \varphi,2\}} = P_{2:3,\ 5,2}\,X^2$$

In this the information is initiated from node 2 and is passed to node 3. From there it goes to 4 and 5 simultaneously. Only the information that reaches 5 is transmitted to the target node 2 but the message reaches 4 is terminated. Hence the corresponding probability cannot be considered.

Rule 5: If the information initiated from the source node and transmitted through any path and reached the target successfully, then the corresponding SDPs are included for reliability computation. This will make the computation monotonous. In order to reduce the length of u-function in PUGF, random weights are introduced based on the step size. That is for each path UGF, the step sizes are identified and based on it, random weights are allotted. For example, if the information is passed successfully in 3 steps, then a weight 3 is allotted to that path. For each random weight, the corresponding probabilities (listed in Table 1) are noted and multiplied with the possibilities. There is one possibility with weight 2, five possibilities with weight 3 and four possibilities are with weight 4. Now WPUGF for node 3 can be obtained as:

$$U(3_w) = \{4\ \ [3_2 P_{2:3,2} + 3_3\ (P_{2:3,4,2} + P_{2:3,5,2} + P_{2:3::\{4,5\}::\{\varphi,2\}} + P_{2:3:\{4,5\}::\{2,\varphi\}} + P_{2:3:\{4,5\}::\{2,2\}}) + 3_4\,(P_{2:3,4,3,2} + P_{2:3,4,5,2} + P_{2:3,5,4,2}\,P_{2:3,5,3,2})]\}\ X^2 = 4\ [1\ [0.03] + 5\ [0.02] + 4\ [0.001]\} = 0.536\ (\text{For SDPs, Table 1})$$

Table 1: The transmission probabilities of the MANET corresponding to random weights

SMs	Sub Source (SS)	Random weights 2	3	4
SM I	2	0.03	0.02	0.001
SM II	6	0.03	0.01	0.002
SM III	10	0.02	0.02	0.001

Rule 6: For a source node (sub source), the UGF for individual and path are same i.e., U (S) = u (S).

Rule 7: Reliability of a sub MANET (R_{SM}) is defined as the probability that the message received at the sub source from the main source has been passed among the group members (nodes) and reached the sub source again:

$$R_{SM} = \sum_{n \subseteq \theta_n} U(n_w)$$

Rule 8: Reliability of the MANET (R_M) is defined as the probability of the transformed message from the source (headquarters) can be passed successfully through the MANET and reached (destroyed) the destination without any delay.

The MANET reliability from source node (headquarters) to the target node D is given by:

$$R_M = \sum R_{SM_i}$$

Rule 9: This rule is used to check the efficiency of the SMs. It calculates the Reliability Ratio (RR). If R_{SM_i}, I = 1, 2,……. denotes the reliability of the corresponding SM, then RR = $R_{SM_i}/R_{SM_{i+1}}$, I = 1, 2,……. If RR>1, then R_{SM_i}, is more reliable than $R_{SM_{i+1}}$, otherwise R_{SM_i}, is reliable.

Algorithm (to calculate the MANET reliability using WUGF): The procedure for reliability evaluation is based on the Universal Generating Function technique, which was introduced by Ushakov (1986) which proved to be very effective for reliability evaluation of various types of multistate systems as seen in Lisnianski and Levitin (2003). Here the focus is to obtain the reliability of a MANET with WUGF.

Step 1: Define the UGF for each sub source (source) of the available sub MANETs:

$$U(S) = \sum_{N \subseteq \theta_n} P_{n:N} X^N$$

Step 2: Define the WUGF for all neighboring nodes except the sub source in each sub groups:

$$U(n) = \sum_i n_i P_{n:N,D} X^D N \subseteq \theta_N$$

Step 3: Composite the path WUGF U (n) as a polynomial in X U (n_w) = u (S) $\otimes$ u (n_w).

Step 4: Compute the reliability of sub MANETs using rule 7.

Step 5: Calculate the reliability of MANET using rule 8.

RESULTS AND DISCUSSION

The case study considered here has been taken into account to check the efficiency of the platoon of soldiers in destruction of a terrorist camp. It involves three sort of soldiers each has a group leader and three members. Destruction of a target (Destination node-D, possibly a terrorist camp) is an assignment given to the three groups. The motive of the assignment is to evaluate the performance efficiency of the groups. The details of the assignment will be commended from the military headquarters (source node-S) to the group leaders at a time (MC). It is the time for the leaders to disseminate the information among their members and make them ready to take part in the assignment. Based on the necessity, the leader and members of each group exchange the information within them and destroy the target. This will be restricted to at a maximum of two times exchange.

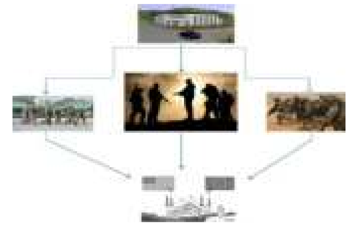


Fig. 3: Battle field environment of this case study

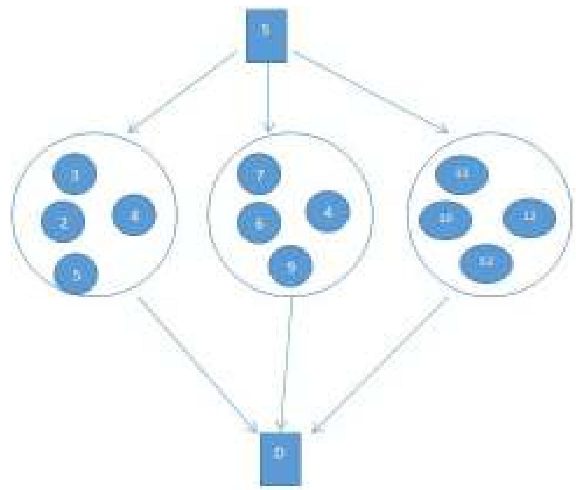


Fig. 4: MANET formation of this case study

This case study can be considered as a MANET with 14 nodes. Out of these nodes the headquarters and terrorist camp are treated as the main source and the destination nodes. Remaining 12 nodes are divided into three SMs each of them with four nodes. Among these four nodes, one will act as sub source (leader) and the others are the participating nodes. As the assignment is to check the efficiency of the groups, the communication between the groups is restricted. Figure 3 expounds this situation.

In Fig. 4 S stands for the headquarters (main source) and D represents the destination (terrorist camp) and the intermediate nodes 2, 6 and 10 denote the group leaders (sub sources). Nodes (3, 4, 5), (7, 8, 9) and (11, 12, 13) are members of SM I, II, III

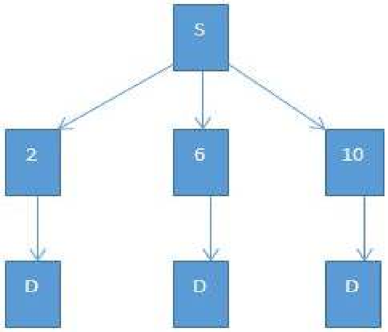


Fig. 5: Message transmission through MANET

respectively. Each sub source together with some participating nodes can be treated as SMs. Here there are 3 SMs.

Figure 5 expounds how messages are transmitted in MANET (Fig. 4). The node S will disseminate the information (multicasting) to the group leaders at a time. Immediately, the nodes 2, 6 and 10 will send the message to their member nodes to get clarity over the mission. Once the clarity is obtained they will attack their destination. The three SMs will involve themselves separately in this mission. In any SM, the member nodes will receive same kind of information a maximum of two times only. For finding the reliability, all the possibilities of transforming information within the SM will be considered.

Table 1 summarizes the Random Weights and the corresponding Transmission Probabilities of the MANET. These weights are assigned based on number of the communications to reach the destination. The novelty algorithm proposed in this study can be applied to the above network (Fig. 4) with the data given in the Table 1.

UGF and reliability calculation for SM I: The node UGF of SM I for source and member nodes 3, 4 and 5 can be obtained by considering all possible communications that receives information directly from the nodes:

$$u(2) = U(2) = P_{2:3}X^{3} + P_{2:4}X^{4} + P_{2:5}X^{5} + P_{2:\{3,4\}}X^{\{3,4\}} + P_{2:3,5}X^{\{3,5\}} + P_{2:4,5}X^{\{4,5\}} + P_{2:\{3,4,5\}}X^{\{3,4,5\}}$$

$$u(3) = [P_{3:2} + P_{3:4,2} + P_{3:5,2} + P_{3:4,3,2} + P_{3:4,5,2} + P_{3:5,4,2} + P_{3:\{4,5\}::\{\varphi,2\}} + P_{3:\{4,5\}::\{2,\varphi\}} + P_{3:\{4,5\}::\{2,2\}} + P_{3:5,3,2}]X^{2}$$

$$u(4) = [P_{4:2} + P_{4:3,2} + P_{4:5,2} + P_{4:3,4,2} + P_{4:3,5,2} + P_{4:5,3,2} + P_{4:\{3,5\}::\{\varphi,2\}} + P_{4:\{3,5\}::\{2,\varphi\}} + P_{4:\{3,5\}::\{2,2\}} + P_{4:5,4,2}]X^{2}$$

$$u(5) = [P_{5:2} + P_{5:3,2} + P_{5:4,2} + P_{5:3,5,2} + P_{5:3,4,2} + P_{5:\{3,4\}::\{2,\varphi\}} + P_{5:\{3,4\}::\{\varphi,2\}} + P_{5:\{3,4\}::\{2,2\}} + P_{5:4,5,2.} + P_{5:4,3,2}]X^{2}$$

The WPUGF of SM I for nodes 3, 4 and 5 can be obtained as follows:

$$U(i) = U(S) \otimes u(i) \text{ here } S = 2,\ i = 3, 4, 5$$

In Fig. 4, the information passed from 2 and transmitted via 3 (or) 4 (or) 5 and again reached 2 will be considered as the successful transformation. There are 4×10 possibilities for a successful communication via 3 in SM I. The possibilities are described as:

$$U(i) = U(S) \otimes u(i) \text{ here } S = 2;\ i = 3$$

$$U(3) = U(S) \otimes u(3) = U(2) \otimes u(3) = \sum_i 3_i P_{2:3,N::2}X^{2}\ N \subseteq \theta_3 = [P_{2:3}X^{3} + P_{2:4}X^{4} + P_{2:5}X^{5} + P_{2:\{3,4\}}X^{\{3,4\}} + P_{2:3,5}X^{\{3,5\}} + P_{2:4,5}X^{\{4,5\}} + P_{2:\{3,4,5\}}X^{\{3,4,5\}}] \otimes [P_{3:2}X^{2} + P_{3:4,2} + P_{3:5,2} + P_{3:4,3,2} + P_{3:4,5,2} + P_{3:5,4,2} + P_{3:\{4,5\}::\{\varphi,2\}} + P_{3:\{4,5\}::\{2,\varphi\}} + P_{3:\{4,5\}::\{2,2\}} + P_{3:5,3,2}]X^{2}$$

$$U(3) = 4\,[P_{2:3,2} + P_{2:3,4,2} + P_{2:3,5,2} + P_{2:3,4,3,2} + P_{2:3,4,5,2} + P_{2:3,5,4,2} + P_{2:3::\{4,5\}::\{\varphi,2\}} + P_{2:3:\{4,5\}::\{2,\varphi\}} + P_{2:3:\{4,5\}::\{2,2\}} + P_{2:3,5,3,2}]X^{2}$$

In the first term the communication is done with 2 steps where as in second, third and seventh to ninth terms it takes 3 steps and for the remaining terms it needs 4 steps. To reduce the length of u-function, weights 2, 3 and 4 are applied based on the mentioned step size. Hence WPUGF for node 3 will be described as:

$$U(3_w) = \{4\ [3_2P_{2:3,2} + 3_3\,(P_{2:3,4,2} + P_{2:3,5,2} + P_{2:3::\{4,5\}::\{\varphi,2\}} + P_{2:3:\{4,5\}::\{2,\varphi\}} + P_{2:3:\{4,5\}::\{2,2\}}) + 3_4\,(P_{2:3,4,3,2} + P_{2:3,4,5,2} + P_{2:3,5,4,2}\,P_{2:3,5,3,2})]\}\,X^{2}$$

The possible communication via node 3 alone in SM I is expounded in Fig. 6a to d.

Figure 6a expounds the various possibilities of passing the information from the sub source 2 in SM I. Here the message received node 2 can be passed to nodes 3 or 4 or 5 or {3, 4} or {3, 5} or {4, 5} or {3, 4, 5} (at a time).

Figure 6b expounds the transmission of message in SM I via node 3. There are several possibilities. The information received at node 3 may send back to source immediately if it requires only two steps. Otherwise the message from node 3 may be passed to node 4 or 5 or {4, 5}. From node 4 (or 5) it may either sent back to source (three steps) or again sent back to 3 (one time repetition is permitted) from there it reaches node 2 (4 steps) or transmitted to node 5 (or 4) then to node 2 (4 steps). But the information received by nodes {4, 5} simultaneously, from both nodes it may reach the target or from any one node (4 or 5) it may reach the target and from the other (4 or 5) it is terminated (3 steps). While calculating the Path UGF for SM 1 via node 3, consider all possible communication that are done via 3

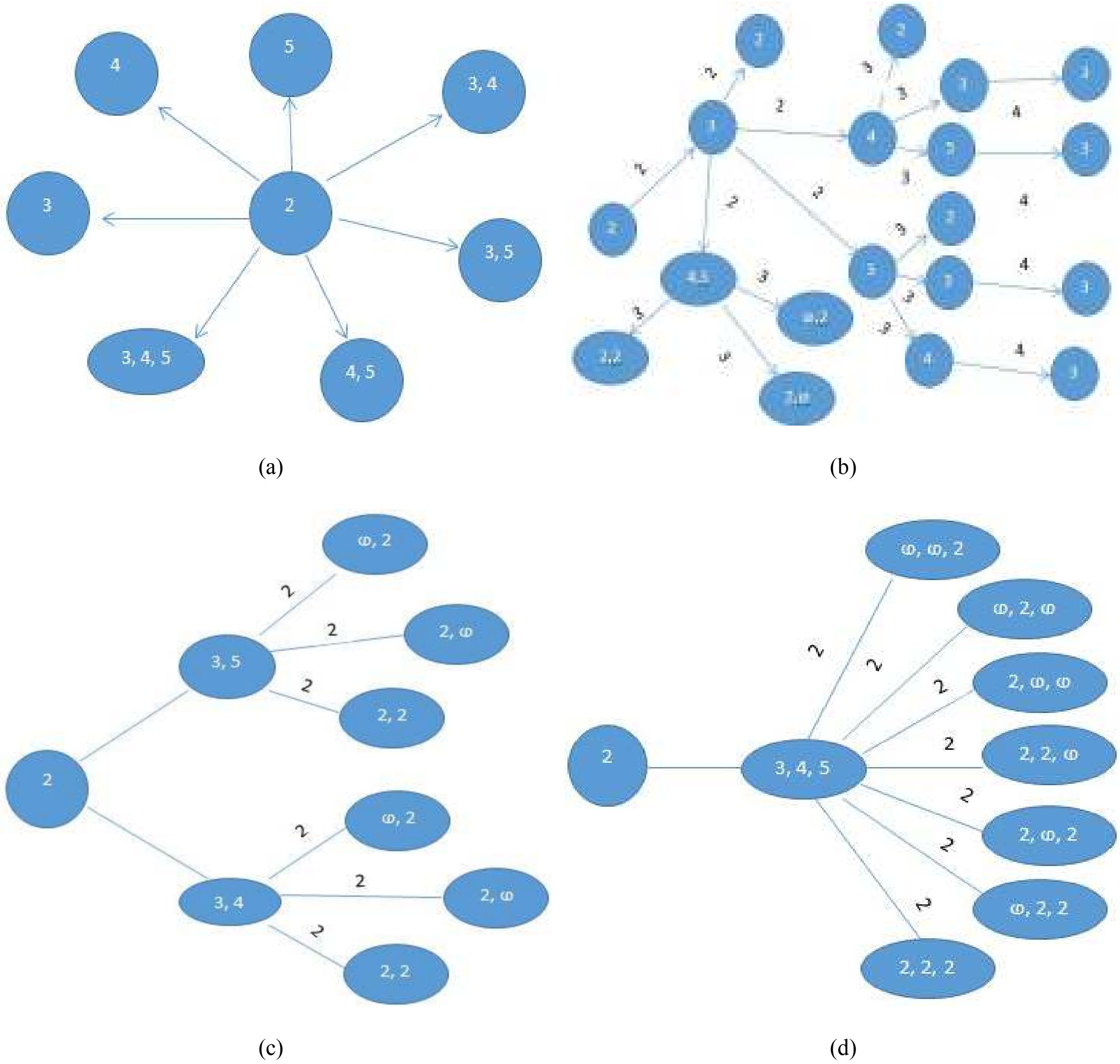


Fig. 6: Message transmission in SM I via node 3

(which includes transmission of messages from 2 to 3, {3, 4}, {3, 4, 5}) and reaches again 2. So weights 2, 3, 4 are assigned to the corresponding paths. Figure 3c and d explains the other possibilities of transmission via node 3 in SM I.

The number of u-functions will be same for nodes 4 and 5. In the same way they are described as:

$$U(4_w) = U(2) \otimes u(4_w) = \sum_i 4_i P_{2:4,N::2} X^2, \; N \subseteq \theta_4$$

$$U(5_w) = U(2) \otimes u(5_w) = \sum_i 5_i P_{2:5,N::2} X^2, N \subseteq \theta_5$$

In reliability calculation via SM I, all the successful transmissions via 3, 4 and 5 are combined. Totally there are three possibilities with weight 2, twenty one possibilities with weight 3 and six possibilities with weight 4.

$R_{SM\ I}$ via nodes 3, 4 and 5 can be calculated as:

$$R_{SM\ I} = U(S) \otimes u(2) = P_{S:2,D} = U(3_w) + U(4_w) + U(5_w) = \{4\,[3_2 P_{2:3,2} + 3_3 (P_{2:3,4,2} + P_{2:3,5,2} + P_{2:3::\{4,5\}::\{\varphi,2\}} + P_{2:3:\{4,5\}::\{2,\varphi\}} + P_{2:3:\{4,5\}::\{2,2\}}) + 3_4 (P_{2:3,4,3,2} + P_{2:3,4,5,2} + P_{2:3,5,4,2} + P_{2:3,5,3,2})] + [4_2 P_{2:4,2} + 4_3 (P_{2:4,3,2} + P_{2:4,5,2} + P_{2:4::\{3,5\}::\{\varphi,2\}} + P_{2:4:\{3,5\}::\{2,\varphi\}} + P_{2:4:\{3,5\}::\{2,2\}} + P_{2:4:\{3,5\}::\{2,2\}}) + 4_4 (P_{2:4,3,4,2} + P_{2:4,3,5,2} + P_{2:4,5,3,2} + P_{2:4,5,4,2})] + [5_2 P_{2:5,2} + 5_3 (P_{2:5,4,2} + P_{2:5,3,2} + P_{2:5::\{4,3\}::\{\varphi,2\}} + P_{2:5:\{4,3\}} + P_{2:5:\{4,3\}::\{2,2\}} + P_{2:5,3,5,2}) + 5_4 (P_{2:5,4,5,2} + P_{2:5,4,3,2} + P_{2:5,3,4,2})]\} X^2$$

$$R_{SM\ I} = 4\,[3x0.03 + 6x0.06 + 21x0.01] = 0.924$$

UGF and reliability calculation for SM II: The node UGF of SM II for nodes 6, 7 and 8 can be obtained as follows:

$$u(6) = U(6) = P_{6:7}X^{7} + P_{6:8}X^{8} + P_{6:9}X^{9} + P_{6:\{7,8\}}X^{\{7,8\}} + P_{6:\{7,9\}}X^{\{7,9\}} + P_{6:\{8,9\}}X^{\{8,9\}} + P_{6:\{7,8,9\}}X^{\{7,8,9\}}$$

$$u(7) = [P_{7:6} + P_{7:8,6} + P_{7:9,6} + P_{7:8,7,6} + P_{7:8,9,9} + P_{7:9,8,6} + P_{7:\{8,9\}::\{\varphi,6\}} + P_{7:\{8,9\}::\{6,\varphi\}} + P_{7:\{8,9\}::\{6,6\}} + P_{7:9,7,6}]\, X^{6}$$

$$u(8) = P_{8:6} + P_{8:7,6} + P_{8:9,6} + P_{8:7,8,6} + P_{8:7,9,6} + P_{8:9,7,6} + P_{8:\{7,9\}::\{\varphi,6\}} + P_{8:\{7,9\}::\{6,\varphi\}} + P_{8:\{7,9\}::\{6,6\}} + P_{8:9,8,6}]\, X^{6}$$

$$u(9) = P_{9:6} + P_{9:7,6} + P_{9:8,6} + P_{9:7,9,6} + P_{9:7,8,6} + P_{9:8,7,6} + P_{9:\{7,9\}::\{\varphi,6\}} + P_{9:\{7,8\}::\{6,\varphi\}} + P_{9:\{7,8\}::\{6,6\}} + P_{9:8,9,6}]\, X^{6}$$

The WPUGF of SM II for nodes 7, 8 and 9 can be obtained as follows:

$$U(i) = U(S) \otimes u(i) \text{ here } S = 6,\ i = 7, 8, 9$$

$$U(7_w) = U(6) \otimes u(7_w) = \textstyle\sum_i 6_i\, P_{6:7,N::6}X^{6},\ N \subseteq \theta_7$$

$$U(8_w) = U(6) \otimes u(8_w) = \textstyle\sum_i 8_i\, P_{6:8,N::6}\, X^{6},\ N \subseteq \theta_8$$

$$U(9_w) = U(6) \otimes u(9_w) = \textstyle\sum_i 9_i\, P_{6:7,N::6}X^{6},\ N \subseteq \theta_9$$

$$R_{SM\ II} = U(S) \otimes u(2) = P_{S:6,D} = U(7_w) + U(8_w) + U(9_w) = \{4\, [7_2\, P_{6:7,6} + 7_3\, (P_{6:7,8,6} + P_{6:7,9,6} + P_{6:7:\{8,9\}::\{\varphi,6\}} + P_{6:7:\{8,9\}::\{6,\varphi\}} + P_{6:7:\{8,9\}::\{6,6\}}) + 7_4\, (P_{6:7,8,7,6} + P_{6:7,8,9,6} + P_{6:7,9,8,6} + P_{6:7,9,7,6})] + [8_2 P_{6,8,6} + 8_3\, (P_{6:8,7,6} + P_{6:8,9,6} + P_{6,8:\{7,9\}::\{\varphi,6\}} + P_{6,8:\{7,9\}::\{6,\varphi\}} + P_{6:8:\{7,9\}::\{6,6\}}) + 8_4\, (P_{6:7,8,7,6} + P_{6:8,7,9,6} + P_{6:8,9,7,6} + P_{6:8,9,8,6)}] + [9_2\, P_{6:9,6} + 9_3\, (P_{6:9,8,6} + P_{6:9,7,6} + P_{6:9:\{8,7\}::\{\varphi,6\}} + P_{6:9:\{8,7\}::\{6,\varphi\}} + P_{6,9:\{8,7\}::\{6,6\}}) + 9_4\, (P_{2:5,4,5,2} + P_{2:5,4,3,2} + P_{2:5,3,4,2} + P_{6:9,7,9,6})]\}\, X^{2}$$

Reliability calculation of Path UGF for SM II via nodes 7, 8 and 9 are as follows:

$$R_{SM\ II} = 4\, [3x0.03 + 6x0.01 + 21x0.002] = 0.6168$$

UGF and reliability calculation for SM III: The node UGF of SM III for nodes 11, 12 and 13 can be obtained as follows:

$$u(10) = U(10) = P_{10:11}X^{11} + P_{10:12}X^{12} + P_{10:13}X^{13} + P_{10:\{11,12\}}X^{\{11,12\}} + P_{10:\{11,13\}}X^{\{11,13\}} + P_{10:\{12,13\}}X^{\{12,13\}} + P_{10:\{11,12,13\}}X^{\{11,12,13\}}$$

$$u(11) = [P_{11:10} + P_{11:12} + P_{11:13,10} + P_{11:12,11,10} + P_{11:12,13,10} + P_{11:13,12,10} + P_{11:\{12,13\}::\{\varphi,10\}} + P_{11:\{12,13\}::\{10,\varphi\}} + P_{11:\{12,13\}::\{10,\quad 10\}} + P_{11:13,11,10\}}]\, X^{10}$$

Table 2: Reliability of various SMs

SMs	Reliability
SM I	0.924
SM II	0.6168
SM III	0.804

$$u(12) = [P_{12:10} + P_{12:11,10} + P_{12:13,10} + P_{12:11,12,10} + P_{12:7,9,10} + P_{12:13,11,10} + P_{12:\{11,13\}::\{\varphi,10\}} + P_{12:\{7,9\}::\{10,\quad \varphi\}} + P_{12:\{11,13\}::\{10,\quad 10\}} + P_{12:13,12,10\}}]\, X^{10}$$

$$u(13) = [P_{13:10} + P_{13:11,10} + P_{13:12,11} + P_{13:11,13,10} + P_{13:11,12,10} + P_{13:12,11,10} + P_{13:\{7,9\}::\{\varphi,10\}} + P_{13:\{11,12\}::\{10,\varphi\}} + P_{13:\{11,12\}::\{10,10\}} + P_{13:12,13,10\}}]\, X^{10}$$

The path UGF for SM III is defined as U (i) = U (S) ⊗ u (i) here S = 10, i = 11, 12, 13:

$$U(11_w) = U(10) \otimes u(11_w) = \textstyle\sum_i 11_i\, P_{10:11,N::10}\, X^{10},\ N \subseteq \theta_{11}$$

$$U(12_w) = U(10) \otimes u(12_w) = \textstyle\sum_i 12_i\, P_{10:12,N::10}\, X^{10},\ N \subseteq \theta_{12}$$

$$U(13_w) = U(10) \otimes u(13_w) = \textstyle\sum_i 10_i\, P_{10:11,N::10}\, X^{10},\ N \subseteq \theta_{13}$$

$$R_{SM\ III} = U(S) \otimes u(10) = P_{S:10,D} = R_{SM\ III} = U(11_w) + U(12_w) + U(13_w) = \{4\, [11_2\, P_{10:11,10} + 11_3\, (P_{10:11,12,10} + P_{10:11,13,10} + P_{10:11:\{12,13\}::\{\varphi,10\}} + P_{10:11:\{12,13\}::\{10,\varphi\}} + P_{10:11:\{12,13\}::\{10,1\}}) + 11_4\, (P_{10:11,12,11,10} + P_{10:11,12,13,10} + P_{10:11,13,12,10} + P_{10:11,13,11,10})] + [12_2 P_{10:12,10} + 12_3\, (P_{10:12,11,10} + P_{10:12,13,10} + P_{10:12:\{11,13\}::\{\varphi,10\}} + P_{10:12:\{11,13\}::\{10,\varphi\}} + P_{10:12:\{11,13\}::\{10,10\}}] + 12_4\, (P_{10:11,12,11,10} + P_{10:12,11,13,10} + P_{10:12,13,11,10} + P_{10:12,13,12,10}] + [13_2 P_{10:13,10} + 13_3\, (P_{10:13,12,10} + P_{10:13,11,10} + P_{10:13:\{12,11\}::\{\varphi,10\}} + P_{6:9:\{8,7\}::\{6,\varphi\}} + P_{6,9:\{8,7\}::\{6,6\}}) + 13_4\, (P_{10:13,12,13,10} + P_{10:13,12,11,10} + P_{10:13,11,12,10} + P_{10:13,12,13,10\}})]\}\, X^{2}$$

$$= 4\, [3x0.02 + 6x0.02 + 21x0.001] = 0.804$$

Hence the reliability of the each SMs with 3 member nodes and one source under the military environment are listed in Table 2. SM I achieves the target with a reliability of 0.924. SM II and III achieve the target with a reliability of 0.6168 and 0.804. Using rule 9, it is clear that SM I is more reliable than SM II and III.

CONCLUSION

It may difficult to obtain the performance levels in many highly reliable modern engineering systems. Some new techniques must be initiated to solve these problems. UGF methods and recursive algorithms are two primary approaches for reliability evaluation of multistate systems. This study concentrates on calculating the MANET reliability using WUGFT. The purpose of introducing the WUGF is to reduce the computation burden. The proposed WUGFT in this study is the first scheme that calculates the MANET reliability. The UGF is used to mathematically represent the sub paths and combine their SDPs through a formally introduced composition operator to find the final MANET reliability. An illustration of this technique has been proved with a case study in a battle field environment. A future development of this technique may include with one or more constraints (cost and time).

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