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Systematic Review for Network Survivability Analysis in MANETS

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Abstract

Network survivability analysis in MANETs was hardly an issue in the early years of wireless technology because there were no critical network system that depended on wireless technology yet. Today, network survivability analysis is an essential aspect of reliable communication especially in MANETs. Although various methods have been proposed to measure network survivability analysis in MANETs, no related review has been published as to date for this topic. Thus, a comprehensive review of this body of work would be beneficial to researchers to have an overview of the current state of research trend in this area. This paper provides a systematic literature review (SLR) of the state of the art approach in network survivability analysis in MANETs. We used studies from a number of relevant article sources, and our results showed the existence of twenty six (26) articles. From this SLR we found that the existing of analysis method is focusing on individual node in which the node is treated as independent event. Furthermore, the analysis also reveals the less popular methods in analyzing network survivability are with statistical methods such as regression analysis and survival analysis. The implication of this study is to give a clear direction to future researchers in this area for a better and accurate analysis in measuring network survivability in MANETs.

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Keywords: Systematic Literature Review; Network Survivability; MANETS

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1. Introduction

Network survivability is a study of availability, dependability and reliability of a physical network topology. It has been discussed as early as in 1970s in the context of military command, control and communication systems. The interest in network survivability has risen in recent years after distributed network such as the mobile ad hoc networks (MANETs) is in high demand (Kumar & Mishra, 2012). In MANETs, network survivability is an essential aspect of reliable communication by providing successful services to maintain network connectivity. It can be referred to the capability of a system to fulfil its mission in a timely manner at the present of attacks, failures or accident (Michele Lima, dos Santos, & Pujolle, 2009; Zhao, Wang, & Wang, 2006). However, survivability in MANETs depends on how well the ad hoc network meets the demands of the survivability requirement. The fundamental requirement for survivability is the ability of the network to provide connectivity between two nodes in an ad hoc network at any instant (Yuan, Chunhe, Haiquan, & Jianzhong, 2009). Connectivity between nodes in MANETs is pivotal due to their self-organizing topology where each node in the network acts as routers and terminals to forward packets to other nodes. Maintaining connectivity is a challenge in the self-organizing nature of the network topology and the dynamic behaviour of nodes such as the frequent occurrence of link and node failures due to interference, mobility, radio channel effect and battery limitation.

In this paper, network survivability model in MANETs is reviewed following systematic literature review (SLR) inspired by (Kitchenham, 2004). Kitchenham defines Systematic Literature Review as "a mean of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest". Systematic literature review is known in the field of software engineering and medical studies, however other fields of study have started using it due to it evidence-based research and the results are derived from scientific experiments, which may be more reliable than mere observations or opinions. In SLR context, evidence means the best quality scientific studies on a specific topic and uses a statistical method to integrate the results. Example of study that applied Kitchenham technique were by (Aleti & Buhnova, 2013) and (Herraiz & Rodriguez, 2013) in software engineering, (Yang & Otaniemi, 2013) in medical study and (Isong & Bekele, 2013) in computer science.

The objectives of this SLR in this paper are threefold; 1) to review systematically the network survivability model in the mobile ad hoc networks, 2) to examine the model and metrics used to analyse network survivability and 3) to highlight open issues for future research in survivability modelling. The structure of this paper is as follows: Section 2 describes the review methods. Section 3 discusses results and analysis of finding in network survivability modelling, survivability metrics and factors. Sections 4 provide a discussion on potential research in network survivability modelling and Section 5 presents the conclusion of this SLR.

2. Review Methods

This section describes the review process undertaken, as illustrated by Fig. 1. The first step involves a process of formulating research questions. Then, search process is presented which includes source of selection and search keywords. Next step is inclusion-exclusion criteria and quality criteria in primary articles. During data extraction steps, the information is extracted, collected and organized in a list. The primary articles are summarized and presented in Section 3 and Appendix A.

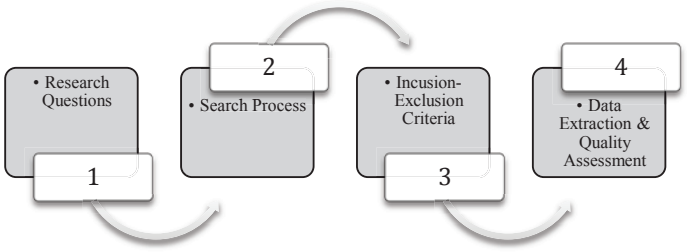

Fig 1: The steps in SLR method.

- *Formulating Research Questions*

The objectives of the review are to answer the following research questions (RQ) in Table 1. With respect to RQ1, the research question tries to answer general view of research trend in network survivability modelling in MANETs. To address RQ1, the number of published journals and conferences dated since 2001 until 2014 are identified. To answer the research question, the main topic and research problems in the studies are analyses. For the purpose of network survivability modelling, RQ2 evaluates the methods used to model network survivability. Thus, three sub-questions are derived to answer RQ2. RQ3 examines the limitation on the current network survivability modelling methods, so that recommendation for future research in the area of network survivability can be used.

Table 1. Research Questions in SLR

RQ#	Research Question Details	
RQ1	What is the current state of knowledge on network survivability modelling in MANETs?	
RQ2	How network survivability is analysed in previous works?	
	RQ2.1	What are the methods used to model network survivability in MANETs?
	RQ2.2	What are the metrics/parameters used to measures network survivability?
	RQ2.3	What factors influence network survivability evaluation?
RQ3	What are the limitations of the current network survivability modelling	

- *Search Processes*

Search process is the most important part in performing SLR. To retrieve articles that are best suited to the research area, the search was done in seven difference phases from the following digital databases:

- IEEE Digital Library
- ACM Digital Library
- Science @Direct
- SpringerLink
- GoogleScholar

The outline of the search process is detailed out in Fig. 2. In Phase 1, five databases mention above are used to search articles that consist of Computer Science and Communication Network. The initial search was using keyword search in the article title and abstract using primary keywords "*Survivability Analysis"* and *"modeling"* and *"MANETs"* or secondary keyword "*Network Survivability"* and *" Evaluation"* and *"MANETs*" in digital databases. The title and abstracts of the retrieve articles were read, and relevant articles were downloaded at Phase 2. Then, thorough readings were done to select relevant articles in network survivability modeling. However, multiple combinations of keywords are identified to describe survivability in literatures. According to (Dimitar et.al, 2004), the network's ability to avoid or cope with failure is measured in three ways: reliability, availability and survivability. Thus, to diversify the selection so that the finding gives accurate result, additional article search is performed using synonym keywords at Phase 4 and Phase 5 by replacing *"survivability"* with *"availability"* and *"reliability"*.

Fig 2 : Search process for SLR.

- *Inclusion-Exclusion Criteria*

Candidate articles are screened against the inclusion and exclusion criteria, before they are considered as primary articles. Table 2 indicates the inclusion and exclusion criteria used to select the primary articles for the final review. In addition, articles that fulfil criteria listed in Table 3 were excluded.

Table 2. Inclusion Criteria

INCL#	Inclusion criteria
INCL1	Survivability, reliability and availability analysis model in MANETs must be the major topic or one of the major topics of the publications
INCL2	Articles should report the method used in network survivability, reliability and availability modelling

Table 3. Exclusion Criteria

EXCL#	Exclusion Criteria
EXCL1	Articles did not focus on network survivability reliability or availability e.g. database survivability, software survivability, and data survivability.
EXCL2	Articles did not present methods of survivability reliability or availability modelling
EXCL3	Short articles, proposals, Lecture Notes, Summary of conference Keynote, Doctorial workshop and tutorial that were not peer-reviewed.
EXCL4	Duplicate articles of the same study are also excluded. Only the most recent article of the same study that was published in a reputable publication is selected.

- *Data Extraction and Quality Assessment*

The purpose of the data extraction is to extract findings in a consistent manner to address the review questions. A data extraction form is required during the course of data extraction to accurately and unbiasedly record the information obtained from selected articles. Table 4 outlines five relevant criteria used to evaluate the quality of the selected articles, inspired by the quality assessment criteria for performing SLR used in (Dybå & Dingsøyr, 2008) and (Salleh, Mendes, & Grundy, 2011). The following ratio scales are used. Yes = 1 point, No = 0 point, Partially = 0.5 point.

Table 4. Quality Assessment Checklist

Item	Answer
QA1: Was the article refereed?	Yes/No
QA2: Was there a clear statement of the objectives of the research?	Yes/No/Partially
QA3: Was there an adequate description of the context in which the research was carried out? For example, clearly stated the problems that leads to the research, descriptions on research methodology used etc.	Yes/No/Partially
QA4: Was the data collection done very well? For example did the evaluation done on proposed approach answered the research questions, did the article provide a thorough discussion on the collected results?	Yes/No/Partially
QA5: Was the simulation results rigorously analysed? For example, is there any survivability metrics provided in evaluating the simulation results?	Yes/No/Partially

3. Results and Discussions

Before the result is discussed, the selection studies are presented first in Section 3.1. Then, in Section 3.2 the result is presented by answering to each research questions in Table 2.

3.1. Selected Studies

From the keyword search, the total of 144 articles collected from journals, conference proceeding, technical reports, part of chapters from online books, articles on web pages and thesis. Only selected articles that are relevant to survivability analysis modelling in MANETs are chosen which down to only 57 articles considered for full article review. From synonym keywords search, 18 additional articles selected after carefully selection in article title and abstract. The return results after inclusion and exclusion criteria gives total final selected articles down to 75 articles as a primary study for this review.

3.2. Network Survivability Research

- RQ1: What is the current state of knowledge on network survivability modeling in MANETs?

To answer this question, analysis will be based on publication years and the quantities of the articles. In Fig. 3, the number of articles presented from year 2001 until 2014 before the quality assessment was done. From the figure, it can be noted that survivability research in MANETs were not the main focus in early years of wireless era, mainly because there were not much application in ad hoc network as wireless technology was still new. Researchers were inclined to focus more on developing routing protocols, MANETs architectures and QoS. When more and more applications or systems are now relying on wireless technology, the research on survivability become demanding from year 2006 to 2014.

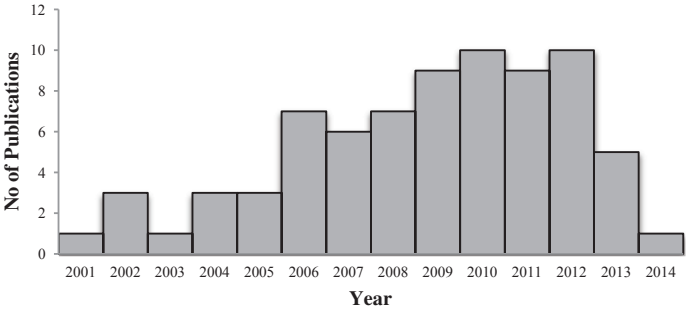

Fig 3 : Numbers of publications (Year 2001-2014)

Based on quality assessment were thoroughly done on criteria listed in Table 3, only 26 articles with quality assessment score of 3.5 and above were meet the criteria needed to answer research question RQ2 and RQ3.

3.3. Network Survivability Modeling

- RQ2: How network survivability is analyzed in previous works?

To specifically answer RQ2, three sub-questions are derived to investigate the available methods of analysing network survivability found in this study.

- RQ2.1: What are the methods used to model network survivability in MANETs*?*

In this study, survivability is modelled qualitatively and quantitatively. Fig.4 shows the distribution of model used in primary study. The figure denotes that 73% use quantitative modelling method, 19% use qualitative modelling method and 8% used both methods. This shows that quantitative modelling has accomplished a strong theoretical background in terms of mathematical model while qualitative model still has room for improvement. Qualitative model involves studying the network survivability by using the methods of conclusion, deduction, and synthetically analysis on the basis of analyser's knowledge and experience (Wang, 2009).

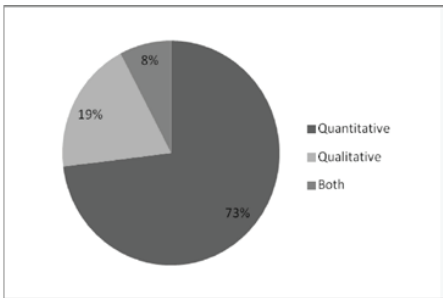

Fig 4 : Survivability model distribution

It gives an integrated framework on engineering for network survivability to describe the abilities and strategies of network to identify, detect and recover from attack, accidents or failures. Analysis shows that there are three types of methods in qualitative modelling in network survivability which deal with route or path restoration, attack detection mechanism and topology control formation.

The study in qualitative modelling involves identifying of essential network components to provide services or satisfying properties that must be maintain during the attacks or failures. It is closely related to measure vulnerability and can be validate with a quantitative methods. Table 5 presents the methods of qualitative model in the study.

Table 5. Qualitative Survivability Methods

Qualitative Methods	Authors
Route or path restoration	Daniel, A. K., Singh, R., & Saini, J. P. (2011) ; Lima, M. & Silva, H. da (2008); Wang, T. et al. (2010)
Attack detection mechanism	Gerhards-Padilla, Elmar & et al. (2007); Zhou, Yihong, Dapeng Wu, and Scott M. Nettles. (2006)
Topology control formation.	Kim, T.H., Tipper, D., Krishnamurthy, P., et Al. (2009)

On the other hand, quantitative model use certain indexes to measure network survivability, and express the analysis results of network survivability through detailed numerical values. The study in quantitative model develops and employs mathematical models and theories to describe network scenarios. These models and theories are applied depending on applications and network evaluation in survivability modelling such as physical topology structure, states-transition and survivability services. Table 6 shows the classification methods for quantitative model with the theory associate to it.

Table 6. Quantitative Survivability Methods

Methods	Theory	Authors
Physical Topology	Random Graph Theory	Kim, T.H., Tipper, D., Krishnamurthy, P., et Al. (2009); Law, Y.W. et al (2007); Xing, F. & Wang, W. (2010) ; Xing, F. & Wang, W. (2007a); Xing, F. & Wang, W. (2011)
	Weighted Graph Theory	Zhang, D. et al. (2012)
State-transition	Markov Chain/ Semi-Markov	Chen, D., Garg, S. & Trivedi, K, (2002); Dimitar, T. et al., (2004); Hwang, S.K. & Kim, D.S, (2006); Kalogridis, G., Square, Q. & Lin, R.,(2009); Park, S., Song, J. & Kim, B.,(2006); Peng, S. et al., (2011); Peng, S. et al., (2008); Thein, T., Lee, S.M. & Park, J.S., (2009); Wang, T. et al. (2010)
Survivability Services	Connectivity Routing End-to-end communication	Kim, T.H., Tipper, D., Krishnamurthy, P., et Al. (2009); Hekmat, R. & Mieghem, P. Van (2004); Lima, M. & Silva, H. da (2008); Peng, S. et al., (2011); Santi (2005); Wang, T. et al. (2010)

- Physical Topology Structure

Survivability model based on network topology structure was the earliest methods in survivability modeling. In this model, the physical topology structure in MANETs was expressed by graph theory where the nodes are the vertex and the physical links are the edges in actual network. The graph can be random or weighted graph. The graph theory assumes that the network is connected if two nodes have an edge connecting to them. The graph theory was used in the study to derive topological survivability in MANETs. In their study, network survivability is mainly determined by node connectivity to forward packets. Any node or link failures could degrade network performance. Weighted graph theory was also used to address the dynamic topology of MANETs. In this case, survivability is measured as a weighted adjacency matrix, in which the weights refer to link availability. This modeling method was directly correlative with ad hoc network physical structure, and was a static and intuitionistic modeling method. The drawback of the graph theory method concerns on the problems of complicated computation, so it could generally deal with small-scale network and be rarely applied in survivability evaluation of large-scale network (Yingkun, Xinhua, & Rulin, 2010).

- States-Transition

Many attacks in MANETs can be described in terms of the conditions or situations that a node can be in a state, how the node moves from one state to another (transition), and how likely the node makes a move (transition probabilities). State-transition modelling method makes use of the state transition diagram to describe the node's

behaviour and its changes. States in MANETs refer to the behaviour of nodes at one particular time, which refers to *t* time. The change of state may be due to various factors. For example, a failed node may be caused by energy depletion or out of transmission range, or may be attacked due to security that has been compromised. The well-known state transition theory is the Markov theory. In Markov theory, the future behaviour of the process depends solely upon the current state and not any one from the past. It can be either a discrete time or a continuous time. However, most research in network survivability modelling adopts continuous time version of Markov chain to describe a stochastic process. This is because the change of state in MANETs is unpredictable and requires continuous data to determine the current state. Markov Chain can also be combined with other mathematical models such as the availability model, performance model, threat/fault model and reliability model to measure network survivability.

- Survivability Services

A key of a survivable network is its capability to deliver essential services even in occurrences of attacks, intrusion, failures or accident. According to (Lima et al., 2009), some essential services in MANETs are providing connectivity, routing and end-to-end communication. These services are expected to be continuously provided even when undesired events such as malicious attacks, natural disasters, or network failures occur. As define by Lima et al. (2008), connectivity is a fundamental requirement for survivability. The connectivity of MANETs is achieved via node degree (Xing & Wang, 2007a; Kim, Tipper & Krishnamurthy, 2009; Peng et al., 2011; Younes & Thomas, 2013), radio propagation (Hekmat, Mieghem, 2004; Lima et al., 2008), and node mobility (Santi, 2005; Xu & Wang, 2006; Younes & Thomas, 2013; T. Wang et al., 2010). On the other hand, routing provides services at physical, medium and data link layer to protect nodes from attackers. Lima and Silva (2008) shows how they were able to solve routing services by tackling survivability from the security perspective. In addition to connectivity and routing services, communication services work with multiple channels and link for path restoration in the case of connection failure. To achieve optimum network survivability so that it covers different layers of attacks or failures, all the services must integrate in a survivability modelling.

- RQ2.2: What are the metrics/parameters used to measures network survivability?

There are several approaches described in primary studies that define and quantify metrics to evaluate network survivability. The value derived from the metrics must be comparable and measureable. In MANETs, metrics mainly refer to an index measuring connectivity, performance, reliability, fault tolerance and security. Connectivity index is closely related to evaluate survivability in topological networks (Brooks R.R. et al., 2007). The articles by (Abbagnale, A., Cuomo, F. & Cipollone, E., 2009, Dimitar, T. et al.,2004; Hekmat, R. & Mieghem, P. Van, 2004; Kalogridis, G., Square, Q. & Lin, R., 2009; Park, S., Song, J. & Kim, B.,2006; Kim, T.H., Tipper, D., Krishnamurthy, P., et al; 2009a) used connectivity to measure network survivability. According to (Ghimire et al.; 2008), the connectivity of nodes depends on the number of nodes and their transmission range. The articles by (Xing & Wang, 2010) considers node distance, radio transmission range and node mobility as the connectivity index. The node connectivity index is important as it can be used to determine if there are isolated nodes within the network as studied by (Xing and Wang, 2006a). On the other hand, performance index indicates an overall network performance when a network is under attacked or there is a node/link failure. Basically, performance makes use of QoS metrics such as throughput, energy consumption, bandwidth, and packet loss. It may be used in all modelling methods in RQ2.1. For example, (Daniel, A. K., R. Singh, & J. P. Saini, 2011) uses performance metric to evaluate survivability in state transition based model, and another work by (Santi, 2005) measures energy consumption in physical topology model.

Node or link in MANETs is subject to failure, thus, evaluation for network reliability is needed. Certain articles use reliability interchangeably with availability; however both terms give the same definition and evaluation metrics (Yu, W & Liu, K., 2005). Reliability index measures maintainability using metrics such as link lifetime, failure rate, radio transmission range and Mean Time to Failure (MTTF). In similar fashion, fault tolerance uses some parameters that are related to reliability index such as MTTF and failure rate. There are also studies on security aspect of ad hoc network as network survivability metrics such as confidentiality, integrity and authenticity. These metrics are used in qualitative model and normally immeasurable. The full set of metrics used in network survivability evaluation is shown in Table 7.

Table 7. Index vs. Metrics/Parameters

Index	Metric/Parameters
Connectivity	Node degree, Distance, Transmission range, Mobility
Performance	Throughput, Energy consumption, Bandwidth , Packet loss
Reliability/Fault-tolerance	Link lifetime, Failure rate, Transmission range, MTTF, MTBF
Security	Confidentiality, Integrity, Authenticity

- RQ2.3 What factors influence network survivability evaluation?

Network survivability in MANETs is most likely affected by either dynamic topology of the networks, faults or attacks.

- Dynamic Topology

Node in MANETs can move arbitrarily (Yuan et al., 2009). Consequently, network topology may change rapidly and randomly. In survivability analysis, mobility, node degree metric has been considered to measure network survivability under dynamic topology. One example caused by node mobility in dynamic topology is node isolation. According to Xu, W. et al. (2006), this factor will destroy the connecting link between two nodes and disconnected the network into partitions. The problem has been discussed by (Xing & Wang 2010; Cucurull et al. 2012). Another example is in a study by (Babu & Singh, 2012) that shows how node mobility creates a fading channel and loses its transmission to a giant network.

- Node and link Fault

Faults may happen in nodes and links. Node faults are the actions that cause the state of the nodes to change. For example, a cooperative node may change to different state of behaviour such as selfish or state of fail due to battery depletion. Node becomes selfish whenever the energy level is below its threshold value (Komathy & Narayanasamy, 2007). Once at selfish state, the node may not forward data packets for the sake of saving its own energy. This cause a degradation of throughput and the node at this state will create a broken link between connecting neighbours. On the other hand, link fault may cause by signal fading effect, which influence the transmission range of node. Due to node mobility, node may change its position that leads to the distance requirement of link layer connection dissatisfaction (Yuan et al. 2009). The change of state that causes node or link faulty will also affect its connecting neighbours. When one node fail, neighbouring nodes will undertake the responsibility the relay packet to other node which caused extra processing and resulted in high energy consumption. This scenario is known as correlated behaviour.

- Security Attacks

There are a wide variety of attacks that target the weakness of MANETs. For example, routing messages are an essential component of mobile network communications, as each packet needs to be passed quickly through intermediate nodes, in which the packet must traverse from a source to the destination. Malicious routing attacks can target the routing discovery or maintenance phase by not following the specifications of the routing protocols. There are also attacks that target some particular routing protocols, such as DSR, or AODV (Lima & Silva, 2008). More sophisticated and subtle routing attacks have been identified in recent articles, such as the blackhole or sinkhole (Xing & Wang, 2007a), Byzantine (Kim, T.H., Tipper, D., Krishnamurthy, P., et al , 2009a), and wormhole attacks (Peng, S. et al., 2011). Researches done by (Xing & Wang, 2010) and (Peng, S. et al., 2011) discuss stochastic analysis on node isolation problems due to blackhole and wormhole attack which lead to the damage of the link connectivity substantially. Due to the lack of security measures during data packet forwarding and the node limited resources, in many ad hoc protocols, an attacker can try overloading the network by injecting junk packets into the route (Yu & Liu 2005; Xu et al. 2006; Gu et al. 2007). To overload a network, the attacker can start sending a large number of data packets; thereby make the network using a lot of resources to transport the junk packets. Another potential attack to overload the network is by broadcasting a lot of subscriptions trying to overload neighbouring nodes when they have to process the new subscription requests in addition to forwarding the data packets. Packet injection attack may significantly degrade network performance as well as reduce network survivability substantially as pointed out by (Xing, 2009) in his research. Table 8 shows the relevant factors that affect network survivability metrics discuss in QR2.2.

Table 8. The Relationship of factors effecting survivability metrics

Factors	Metrics	Methods
Dynamic Topology	Node mobility, Node degree	Physical Structure
Node and Link Fault	Energy Consumption, Packet loss, Throughput, Bandwidth	State-transition
Security Attacks	Authenticity	Survivability Services

4. Research Limitation

- *RQ3: What are the limitations of the current network survivability modelling?*

The first limitation found lacking in this study is metric of survivability measurement. The metrics used in survivability model treats node or link behaviours as independent events during the evaluation phase. As discussed in all research articles such as in (Dimitar, T. et al., 2004; Xing & Wang, 2010; Peng, S. et al., 2011) , the analysis assume that node behaviour activities are equally likely and their activities are mutually independent. These assumptions do not adequately reflect the nature of real ad hoc network environment. For example, (Neumayar & Modiano , 2010) highlighted that some of node failures happen as a result of other earlier failures. This is called a correlated node behaviour where failures are due to energy depletion or nodes are moved outside of the transmission range that create chain reaction. Xing and Wang (2010) also mentioned the correlated node behaviour as one of the factors that affect network survivability in their work. However, no further research was carried out to evaluate network survivability under correlated node behaviour scenario.

This study on network survivability modelling has strong theoretical background mainly in graph theory to measure network survivability under connectivity. From Fig.5 above, it shows that the major contribution of network survivability research is either in qualitative or quantitative method. However, statistical method of survivability analysis is not yet being explored. To the researcher's opinion, statistical methods of survival analysis used in medical research have great potential to be explored under network survivability in MANETs. Yet, the survivability study was first being used in medical research to measure survival or failure times of an event or time-to-event in a better term. Examples of time-to-event are the lifetimes machine components, survival time of cancer patients, occurrences of the next traffic accident, or duration of economic recessions (Diva, Banerjee, & Dey, 2007; Z. Ma & Krings, 2008). Moreover, survival analysis is also suitable to study applications in computer science, such as in network reliability and survivability (Ma et al. 2008; Sunilkumar et al. 2011; Zhang et al. 2013). According to (Ma et al, 2008), survival analysis and reliability theory have the exact same mathematical models in their basic definitions. Thus, it is feasible to develop a theory of network survivability in MANETs that can be put into survival analysis model as in biomedical research.

5. Conclusion

A systematic literature review was conducted in this paper to understand the issues related to network survivability analysis model in MANETs. This paper has explained the process of selecting and reviewing literature according to Kitchenham style. The literature review has covered the issues on network survivability modeling such as the metrics used to measure survivability and the factors that caused network to be in critical condition. It is noted from the literature on survivability modeling that network survivability practices still fixates the theoretical works, with much work on ensuring connectivity of nodes to guarantee network performance will not degrade. Little work is done to encounter correlated attack as this attack has severe impact on network survivability. As wireless technology keep growing, more challenges need to be addressed. The new identified challenge is in the area of biomedical science. A lot of biomedical theory can be applied to computer science research especially in the area of survivability and security, such as the epidemic theory, survival analysis and the immune system theory. Thus, there is no doubt that network survivability and biomedical science will be one of the most interesting and challenging areas of this research.

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