On Reliability of Networked Systems: Methods for Mobile Ad-hoc Wireless Networks

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Abstract- The advancement of the self-forming, multi-hop Mobile Ad-hoc Wireless Networks (MAWN) creates the need for new analysis methods which enable the accurate determination of the reliability and availability of these networked systems. Contrary to hardwired networks, MAWN is a scalable network without infrastructure. Along this line, the MAWN’s configuration forms dynamically and probabilistically and as such no singular graphical depiction or mathematical function is able to describe its reliability. A set of new methods and thus new research is required in parallel with the proliferation of this technology so that reliable performance may be realized.

1. Introduction

The Mobile Ad-hoc Wireless Network (MAWN) is rapidly becoming the preferred solution for flexible and low cost networking. In addition, due to its flexibility, this new network scheme is often deployed in critical applications such as military and first responder applications. In such cases, reliability becomes a paramount system attribute. However, to achieve system reliability the practitioner must first be able to define and measure this metric. The MAWN does not conform to the basic assumptions on which existing network reliability methods are founded and so, these same methods are inappropriate. The feature that precludes the use of traditional methods is the MAWN’s absence of infrastructure items (e.g. routers, base stations).

For hardwired and infrastructure based wireless networks (cellular networks as an example) the configuration of a network is known and constant. In other words, the structure of the network in terms of component connectivity is known \textit{a-priori}. Accordingly, the
component-wise relationship to reliability can be depicted graphically with methods such as the reliability block diagram (RBD) and the fault tree analysis (FTA) method. On the other hand, a MAWN consists of only mobile nodes that dynamically form a network. The absence of infrastructure in a MAWN results in a network with no predetermined connectivity; all network nodes are mobile and may be connected to each other. The effect is that any permutation of the node-pair links may result when the network forms and reforms. The amount of possible permutations grows quickly with the number of nodes. For large networks the enumeration of all possible permutations is not practical so in this case simulation is leveraged. Even when all permutations are enumerated, exact prediction of which permutation will actually be present at any time is not possible. However, it is possible to predict the formation of a given network configuration probabilistically. This concept will form the basis of the proposed research agenda.

The set of methods to be developed under this research agenda will be new and innovative, but more importantly they will contribute to the field by way of their utility. The importance of reliability as a system attribute varies depending upon the nature of the system in question. The reliability of a MAWN is paramount in its prevailing applications; DoD and First Responder networks. For these applications, ad-hoc networking allows for the deployment of tactical networks in areas that are either too harsh or unstable to emplace permanent network infrastructure. It provides the life-line for the users of this technology which employ it in safety critical applications.

2. Research Focus and Existing Work

Much research has been done in areas complementary to this topic. The literature reviewed in classified into five main areas; with a fair degree of overlap between them. The areas include: network reliability analysis and modeling (e.g. Monte Carlo); capacitated
(a.k.a. multi-state) network reliability; node mobility; MAWN protocol performance; and wireless link capacity. However, despite the abundance of related research in these areas, there remains a void. There are no methods that may be applied directly to the study of MAWN reliability. Moreover, few researchers in the field of reliability acknowledge ad-hoc networking at all. Similarly, few researchers in the area of ad-hoc networking refer to reliability in its pure form. Some authors use the word reliability as a qualitative description of a network or protocols overall quality but few use it as the probabilistic measure that it represents herein.

2.1 Network Reliability

The predominant measures of reliability when applied to networks are mainly specialized cases of $k$-terminal reliability. This is defined as the probability that a path exists and connects $k$ terminals (nodes) within the network. Two terminal and all-terminal reliability are popular modifications on this a measure where $k = 2$ and $k=n$ (where $n$ is the number of nodes in the network), respectively. Researchers have published mainly methods applying this definition: including calculation, approximation, optimization, and other variations on these themes [1,2,3].

2.2 Capacitated Network Reliability

This field is an extension or specialization of the research in network reliability. These authors acknowledge that not all links (edges) may have the same capacity (weight); see as an example [4]. In a communications context; not all links will offer the same data rate; e.g. bits per second. Further, some of these authors also consider that the capacity demanded of the network is variable.

2.3 Node Mobility
Of late, the primary focus on node mobility research has been in conjunction with performance models for network protocols and architectures with mobile nodes. This includes cellular networks in addition to the MAWN, as an example see [5]. At least one researcher [6] has published research using mobility models to analyze the reliability of a cellular network. Most mobility models may be classified into two groups: individual (entity) and group mobility models [7]. The individual models represent the motion of each node and this mobility is independent of the motion of each other node in the network. Group mobility models, on the other hand, represent nodes that travel in groups so that the mobility of a node influences and is influenced by the mobility of the other nodes in its group.

2.4 MAWN Protocols

MAWN protocols are still early in their maturation, many researchers are still working to optimize and refine protocols so they may be implemented for the intended applications; for a exhaustive survey of these efforts see [8]. Challenges that are still being addressed include: limiting the network capacity consumed by routing and MAC overhead, resiliency to different mobility patterns, scalability (ability of network to increase total node count), and the assurance of Quality of Service and information security.

2.5 Wireless Link Capacity

Finally, research into the capacity of wireless communications channels has been a topic of research for many decades. One of the shaping works in the area spawned much of the current research; specifically the relationship known as Shannon’s Law [9] is the basis of much of the current research [10,11,12].

3 Research Plan

This body of work will include research into all of the above fields; and likely some others. This literature review will give way to research focused developing new and modified
methods that are accurate and appropriate for the MAWN. That is, the methods developed and published will account for the characteristics of the MAWN that make existing methods in reliability inadequate.

3.1 Probabilistic Network Configuration

The first publishing and fundamental basis for this research focuses on a method that acknowledges a probabilistic formation of the MAWN topology and its susceptibility to change. Analytical and simulation based methods are proposed to account for this aspect. The methods are useful to the practitioner because it enables the analysis of a MAWN’s reliability when certain system and node attributes are known. These include: node reliability, node count, and the probability of link existence between node pairs. Similarly, with this method the designer is now capable of setting and optimizing these input parameters such that reliability objectives are met. Figure 1 depicts two network configurations and the Reliability Block Diagram (RBD) for each. This method enumerates the potential configurations, the probability each would exist, and the resultant MAWN two-terminal reliability (2TR_m).

![Network Configuration Diagram]

3.2 Concurrent Mobility and Reliability Modeling

The next contribution will be to further refine the probability of link existence. In the original method this value is an input parameter to the analytical and simulation models. A new method will remove this parameter and replace it with embedded mobility models.
Figure 2 depicts the vectors to represent the motion of nodes 1 and 2 and then the new configuration that results as they assume new positions.

![Figure 2. Mobility Affect on Network Configuration](image)

The added value with this extension is the understanding gained when mobility parameters (e.g. node speed) can also be analyzed and their affects on the reliability of an ad-hoc network may be determined.

### 3.3 Concurrent Mobility, Reliability, and Demand Modeling

In this section, greater insight into the link status is pursued by incorporation of wireless channel capacity relationships and analysis of the effects of demanded and offered data rates. The suitability of a wireless channel to support the transport of data from a source to destination is dependent on two factors – the demanded data rate and the available data rate. In most applications, the demand is not constant and may be very volatile. Similarly, in a MAWN the available capacity is variable based upon node location and other factors. Here the practitioner is given the capability to simultaneously determine the impacts of node mobility and message traffic profiles because link status is no longer binary rather the available capacity is calculated based upon node positions.

### 3.4 Cluster-based Network Reliability

A MAWN of practical scale often requires some segmentation, typically termed clustering, for successful implementation. The reasons are primarily related to network performance. The cluster-based network is best described as many smaller networks joined together to form a single and cohesive network of networks (see Figure 3). These clusters are
joined when nodes, usually referred to as gateways, form links between clusters. This section will allow the practitioner to analyze the reliability of cluster based ad-hoc networks with a Monte Carlo based approach. It will also provide insight into the affects to reliability due to design decisions on cluster size and gateway assignment.

Figure 3. Cluster based MAWN

3.5 Optimization

In this section a method to optimize a fixed network configuration with minimum cost to meet all-terminal reliability goals will be developed. The “cost” metric will be made flexible so it may be applied as any metric logical to minimize (e.g. size, weight, or cost). This same optimization method will then be applied to the cluster based reliability method to optimize the number and assignment of gateways while achieving a minimum reliability.

4 Contributions

The primary contribution to the field will be the publication of distinctly defined metrics for MAWN reliability and innovative methods to measure them. The practitioners will be given the tools to analyze and optimize MAWN reliability and therefore the ability to influence and improve it. The MAWN is still a break through technology; however, as it matures reliability will be expected and demanded by its users. Mostly, this work is motivated by the application
of MAWN technology in the DoD tactical networks and the import of their reliable operation when employed for this use.

References