System Engineering Approach in Tactical Wireless RF Network Analysis with Vulnerability Assessment using Bayesian Networks

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***Abstract* — Apply systems engineering approaches to measure and analysis vulnerabilities of military tactical RF wireless networks. Develop smart and innovative performance matrixes through EW modeling and simulation scenarios. Systematic utilize of systems engineering approaches with RF electronic warfare modeling and simulation scenarios to support research in vulnerability analysis. RF electronic warfare models are used to provide a practical yet simple process for assessing and investigate the vulnerability of tactical RF systems. The focus is on military or tactical wireless network within a system of systems (SoS) context research area. Wireless RF communication network vulnerabilities critically studied within Department of Defense (DoD) organizations to provide a comprehensive network vulnerability assessment approach. Researchers have proposed a variety of methods to build network trees with chains of exploits, and then perform normal post-graph vulnerability analysis. This paper presents an approach to use Bayesian network to model, calculate and analyze all potential vulnerability paths in wireless RF networks.**

Keywords — System Engineering, Wireless Network Analysis, Vulnerability Assessment, Bayesian Networks

I. INTRODUCTION

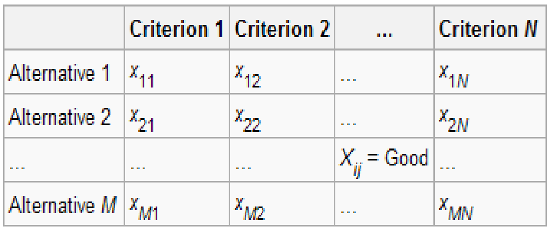
Tactical wireless network vulnerabilities continually being reported and critically studied within Department of Defense (DoD). A comprehensive network vulnerability assessment using systems engineering approach [14] has been an increasing challenge to research analysts. Researchers have proposed a variety of ways to manage network nodes and trees with possible chains of events, and then perform normal post-graph vulnerability assessment and analysis. The most recent system engineering approaches are building attack trees by trying to number all potential attack paths with vulnerabilities identification, node probabilities calculations, inference analysis, weights assignments by system experts. These are expert driven vulnerabilities analysis. Assessment and identification are one of the main key issues in making sure the property security of a given deployed tactical RF communication network. The vulnerability assessment process involves many uncertain factors reside within both the networks and the network nodes. Threat assessment or injecting threats is one of the major factors of evaluating a situation for its suitability to support decision-making and the indication of the security of a given tactical RF communication network system. One approach is using experienced decision makers database. This type of expert driven database recorded most of their decisions on vulnerability identification. The decision-makers use past experience for their decisions. The decision will be based upon previously good solutions that have worked in similar real life scenarios. The approach is to extract the most significant characteristics from the lay-down situation. Any similar situations and actions that have worked well in past cases will be considered in the assessment due to the present or the lack of certain essential characteristics. The assessment and identification is to create relevant relations between objects in the tactical RF network environment. Tactical communication RF wireless networks are best illustrated by David L. Adamy [1]. Bayesian network (BN) and the related methods [7] is an effective tool for modeling uncertainty situation and knowledge. This paper discusses Bayesian' Theory [7], Bayesian networks and their ability to function in a given tactical RF communication network [1] for vulnerabilities analysis and identification. This short paper presents an approach to use Bayesian network to model all potential vulnerabilities or attack paths in tactical RF wireless network. We will call such graph as "Bayesian network vulnerabilities graph" for a given tactical RF wireless network. It provides a more compact representation of attack paths than conventional methods. Bayesian inference methods can be used for probabilistic analysis. It is necessary to use algorithms for updating and computing optimal subsets of attack paths relative to current knowledge about attackers. Tactical RF wireless models were tested on a small example JCSS [2] network. Simulated test results demonstrate the effectiveness of approach.

II. SYSTEMS ENGINEERING APPROACH

Systems engineering is employed here to look into wireless network vulnerabilities with simulation and modeling work-processes. A set of useful tools are developed to handle the vulnerability analysis part of the RF wireless network. In the research, we have summarized a variety of methods to build network trees with chains of possible exploits, and then perform normal post-graph vulnerability assessment and analysis. Recent approaches suggest building more advanced attack trees by trying to number all potential attack paths with vulnerabilities identification, node probabilities calculations, inference analysis, weights assignments by system experts. Vulnerabilities analysis, assessment and identification are one of the key issues in making sure the security of a given tactical RF communication network. The vulnerability assessment process involves many uncertain factors. Threat assessment is one of the major factors of evaluating a situation for its suitability to support decision-making and the indication of the security of a given tactical RF communication network system. Systems engineering methodology in the research plays a critical role to help develop a distinctive set of concept and methodology for the vulnerability assessment of tactical RF communication networks. Systems engineering approaches have been developed to meet the challenges of engineering functional physical systems of tactical RF communication networks with complexity. The system engineering process employs here is a brand of holistic concept of system engineering processes. With this holistic view in mind, the systems engineering focuses are on analyzing and understanding the potential Department of Defense (DoD) customer needs. Re-useable RF connectivity models with requirements and functionality are implemented early in the development cycle of these RF communication network models. We then proceed with design synthesis and system validation while considering the complete problem, the system lifecycle. Based upon the concept by Oliver et al. [13], systems engineering technical process are adopted during the course of the research. Within Oliver's model [13], the technical process includes assessing available information, defining effectiveness measures, to create a behavior Bayesian vulnerabilities model, create a structure model, perform trade-off analysis, and create sequential build & test plan. At the same time, a RF communication system can become more complex due to an increase in network size as well as with an increase in the amount of vulnerabilities data, engineering variables, or the number of fields that are involved in the analysis. The developments of smarter matrices with better algorithms are the primary goals of the research. With disciplined systems engineering, it enables the use of tools and methods to better comprehend and manage complexity in wireless RF network systems for in-depth analysis. These tools are developed using modeling and simulation methodologies, optimization calculations and vulnerabilities analysis. Taking an interdisciplinary engineering systems approach to perform vulnerabilities analysis using Bayesian graph with weights calculation is inherently complex. The behavior of and interaction among RF wireless network system components can be well defined in some cases. Defining and characterizing such RF communication systems and subsystems and the interactions among them which supports vulnerabilities analysis is one of the goals of the research.

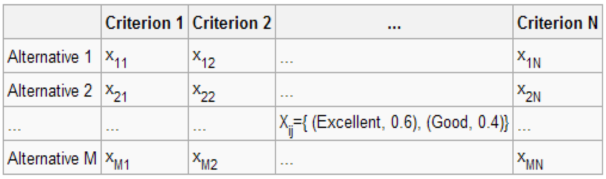
III. IDEAS BEHIND THE RESEARCH

Decision matrix is used for vulnerabilities analysis in the research. Decision matrix is an arrangement of related qualitative or quantitative values in terms of rows and columns. It allows our research to graphically identify, analyze, and rate the strength of relationships between sets of information in vulnerabilities. Elements of a decision matrix represent decisions based upon calculations and Bayesian network (BN) on certain vulnerabilities decision criteria. The matrix development is especially useful and critical for looking at large sample numbers of decision factors and assessing each factor’s relative importance. Decision matrix employs in the research is used to describe a multi-criteria decision analysis (MCDA) for the tactical RF wireless network. When given a MCDA problem, where there are M alternative options and each need to be assessed on N criteria, can be described by the decision matrix which has M rows and N columns, or M × N elements. Each element, such as Xij, is either a single numerical value or a single grade, representing the performance of alternative i on criterion j. For example, if alternative i is "Wireless Node i", criterion j is "Background Noise" assessed by five grades {Excellent, Good, Average, Below Average, Poor}, and " Wireless Node i" is assessed to be "Good" on "Background Noise", then Xij = "Good". The matrix is shown below:



	Criterion 1	**Criterion 2**	**...**	**Criterion *N***
Alternative 1	x_{11}	x_{12}	...	x_{1N}
Alternative 2	x_{21}	x_{22}	...	x_{2N}
...	...	...	X_{ij} = Good	...
Alternative *M*	x_{M1}	x_{M2}	...	x_{MN}

Using a modified belief decision matrix, the research is now more refined and the matrix can describe a multiple criteria decision analysis (MCDA) problem in the Evidential Reasoning Approach. In decision theory, the evidential reasoning approach is a generic evidence-based multi-criteria decision analysis (MCDA) approach for dealing with problems having both quantitative and qualitative criteria under various uncertainties. This matrix may be used to support various decision analysis, assessment and evaluation activities such as wireless RF networks environmental impact assessment and wireless RF networks internal nodes (transceiver) assessment based on a range of quality models that are developed. For a given MCDA, there are M alternative options and each need to be assessed on N criteria, then the belief decision matrix for the problem has M rows and N columns or M X N elements. Instead of being a single numerical value or a single grade as in a decision matrix, each element in a belief decision matrix is a belief structure. For example, suppose Alternative i is "Wireless Node i", Criterion j is "Background Noise" assessed by five grades {Excellent, Good, Average, Below Average, Poor}, and "Wireless Node i" is assessed to be “Excellent” on "Message Completion Rate" with a high degree of belief (i.g. 0.6) due to its low Transmission Delay, low Propagation Delay, good Signal-to-Noise Ratio and low Bit Error Rate. At the same time, the quality is also assessed to be only “Good” with a lower degree of confidence (i.g. 0.4 or less) because its fidelity and "Message Completion Rate (MCR) can still be improved. If this is the case, then we have X_{ij}={ (Excellent, 0.6), (Good, 0.4)}, or X_{ij}={ (Excellent, 0.6), (Good, 0.4), (Average, 0), (Below Average, 0), (Poor, 0)}. A conventional decision matrix is a special case of belief decision matrix when only one belief degree in a belief structure is 1 and the others are 0. The modified matrix is shown below:

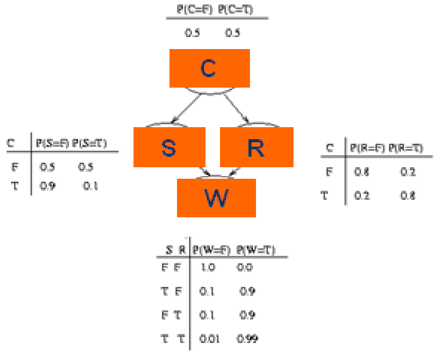


	Criterion 1	Criterion 2	...	Criterion N
Alternative 1	x_{11}	x_{12}	...	x_{1N}
Alternative 2	x_{21}	x_{22}	...	x_{2N}
...	...	...	X_{ij}={ (Excellent, 0.6), (Good, 0.4)}	...
Alternative M	x_{M1}	x_{M2}	...	x_{MN}

The research may help to develop a more systematic and automated approach for building “Bayesian network vulnerabilities graph” with weights assignment for vulnerability study in tactical wireless RF networks [1]. Bayesian network [7] is designed in vulnerabilities graph and models all potential attack steps in a given network. As describe by T. Leonard and J. Hsu [7], using Bayes’ rule as a special case involving continuous prior and posterior probability distributions and discrete probability distributions of data, but in its simplest setting involving only discrete distributions, the theorem relates the conditional and marginal probabilities of events A and B, where B has a certain (non-zero) probability:

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}.$$

Each term in the theorem has a conventional name: P(A) is the prior probability or marginal probability of A. It is "prior" in the sense that it does not take into account any information about B. P(A|B) is the conditional probability of A, given B. It is also called the posterior probability because it is derived from or depends upon the specified value of B. P(B|A) is the conditional probability of B given A. P(B) is the prior or marginal probability of B, and acts as a normalizing constant. The theorem in this form gives a mathematical representation of how the conditional probability of even A given even B is related to the converse conditional probability of even B when given even A. In our research, each wireless network node represents a single security and vulnerability point and contains property violation mode; each link edge corresponds to an exploitation of one or more possible vulnerabilities and each network path represents a series of exploits that can signify a potential vulnerability for attack within the RF wireless network. The communication model takes on characteristics of a tactical wireless RF network, and we consider an integrated posterior probability of Bayesian networks (BN) [7] with well-defined security metric represents a more comprenhsive quantitative vulnerability assessment of a given tactical RF network which contains different communication stages. Posterior probability is a revised probability that takes into account new available information. For example, let there be two stages within a given wireless transceiver. Wireless stage A having vulnerability or 0.35 accuracy due to noise factor and 0.85 accuracy due to jamming factor and wireless stage B having vulnerability or 0.75 accuracy due to noise factor and 0.45 accuracy due to jamming. Now if wireless stage is selected at random, the probability that wireless stage A is chosen is 0.5 (50% chance, one out of two stage). This is the a priori probability for the vulnerability of wireless communication stage. If we are given an additional piece of information that a wireless stage was chosen at random from the wireless network, and that the factor is noise, what is the probability that the chosen wireless stage is A? Posterior probability takes into account this additional information and revises the probability downward from 0.5 to 0.35 according to Bayes' theorem. Also, the noise factor effect is more probable from stage B (0.75) than stage A (0.35). When the factor is jamming instead, the probability that the chosen wireless stage is A will be revised upward from 0.5 to 0.85 instead. Then, the vulnerability related jamming factor now is definitely less probable from stage B (0.45) than stage A (0.85). With conditional independence relationship encoded in a Bayesian network (BN) can be stated as follows: a wireless node is independent of its ancestors given its parents, where the ancestor/parent relationship is with respect to some fixed topological ordering of the wireless nodes. Using figure 1 below to demonstrate the outcomes, by the chain rule of probability with stages C, S, R & W, the joint probability of all the nodes in the vulnerabilities graph is now become: P(C, S, R, W) = P(C) * P(S|C) * P(R|C,S) * P(W|C,S,R). By using conditional independence relationships, we can rewrite this as: P(C, S, R, W) = P(C) * P(S|C) * P(R|C) * P(W|S,R) where we are allowed to simplify the third term because R is independent of S given its parent C, and the last term because W is independent of C given its parents S and R. We can see that the conditional independence relationships allow us to represent the joint more compactly. Here the savings are minimal, but in general, if we had n binary nodes, the full joint would require $\mathbf{O(}{}_{2}n\ N\,\mathbf{)}$ space to represent, but the factored form would require $\mathbf{O(n}\ {}_{2}k\,\mathbf{)}$ space to represent, where k is the maximum fan-in of a node with fewer overall parameters.



P(C=F)	P(C=T)
0.5	0.5

C	P(S=F)	P(S=T)
F	0.5	0.5
T	0.9	0.1

C	P(R=F)	P(R=T)
F	0.8	0.2
T	0.2	0.8

S	R	P(W=F)	P(W=T)
F	F	1.0	0.0
T	F	0.1	0.9
F	T	0.1	0.9
T	T	0.01	0.99

Figure 1: Vulnerabilities graph
(simple stage within a wireless node)

In the model, we concern the vulnerability of the wireless network caused by the failure of various communication stages in the wireless RF communication network. Figure 2 clearly presents the logical communication block diagram of our RF model. Each stage in a RF network is profiled with network and system configurations with exhibited vulnerabilities. They are identified through the breaking down of a given transceiver into transmitter and receiver with different stages. The purpose of our modeling and simulation goals is to make use the DISA JCSS Transceiver Pipeline stages [2]. All vulnerabilities data may be collected and the following information may be collected at run-time: (1) Effect of the transmission on nodes in the vicinity. (2) Set of nodes will attempt to receive the packet. (3) Determine a node attempting to receive a packet successfully. (4) Time it take for a packet to be transferred to the receiver. To start with the transmitter, we break down the transceiver into different radio pipeline stages. On the transmitter side, the transmitter has a “Group Receiver” start with the index “Group 0”. The transmitter executed once at the start of simulation for each pair of transmitter and receiver channels or dynamically by OPNET JCSS’s [2] Kernel Procedure (KP) calls. Inside the radio pipeline stages of the receiver side, for every receiver channel which “passed” the transmission checks, the simulated RF packet will "flow" through the pipe. Using JCSS [2] and OPNET Modeler, it is very critical to make sure the JCSS Radio Pipeline Model [2] attributes are being configured correctly. This is particular important for military RF radios like EPLRS [2] during a lay-down of network nodes in different scenarios. In all cases, configuration should be retained and saved in the node model. In summary, for Radio Transmitter, there are six (6) different stages (stage 0 to stage 5) associated with each Radio Transmitter. The following are six of the stages for a give Radio Transmitter (RT): Receiver Group, Transmission Delay, Link Closure, Channel Match, Transmitter (Tx) Antenna Gain and Propagation Delay. As for the Radio Receiver, there are altogether eight (8) stages (stage 6 to stage 13) that associated with a Radio Receiver (RR): Rx Antenna Gain, Received Power, Interference Noise, Background Noise, Signal-to-Noise Ratio, Bit Error Rate, Error Allocation and Error Correction. In JCSS [2] and OPNET Modeler, there are altogether 14 Pipeline Stages (PS) that have implemented vulnerabilities graph for Bayesian networks (BN) [7] analysis. These are customized collections sequence of ‘C’ or ‘C++’ procedures (code & routines) with external Java subroutines and portable applications written for research purposes. In figure 2, each 14 different stages that comprised in a transceiver network perform a different calculation. For example in (1) Line-of-sight, (2) Signal strength & (3) Bit errors rates. Pipeline Stages (PS) code & routines are written in C, C++ and with external subroutine interfaces written in Java. Each procedure has a defined interface (prototype) with arguments typically a packet. Unlike most available vulnerability bulletins on public domains, we classify tactical wireless networks with vulnerabilities inside the 14 different stages of a given tactical wireless RF communication transceiver. So the vulnerabilities graph for a given tactical transceiver may be classified as vulnerabilities in Radio Transmitter are: (Vt1) Receiver Group, (Vt2) Transmission Delay, (Vt3) Link Closure, (Vt4) Channel Match, (Vt5) Transmitter Antenna Gain and (Vt6) Propagation Delay. On the hand the vulnerabilities for the Radio Receiver are: (Vr1) Rx Antenna Gain, (Vr2) Received Power, (Vr3) Interference Noise, (Vr4) Background Noise, (Vr5) Signal-to-Noise Ratio, (Vr6) Bit Error Rate, (Vr7) Error Allocation and (Vr8) Error Correction.

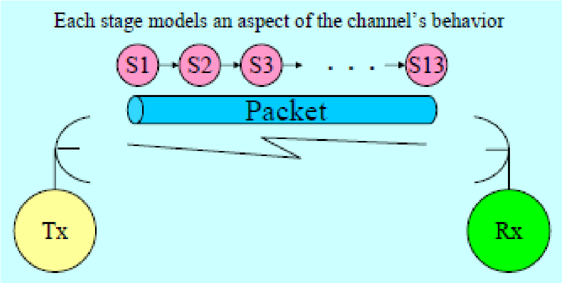
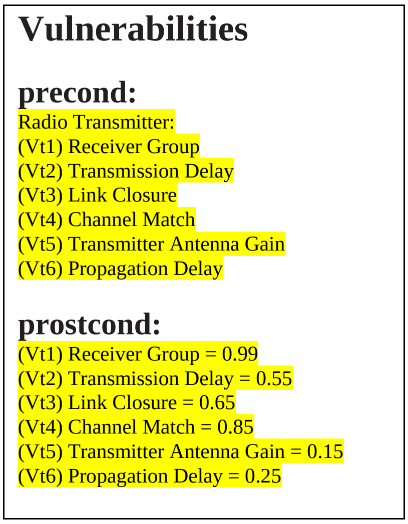


Figure 2: JCCS pipeline stages are defined for a wireless communication model

Using the existing JCSS tactical RF hosts configuration and profile editors with wireless networking analysis tools [3] [4], we can construct generic, vulnerabilities graph and templates to describe possible exploitations conditions with certain vulnerabilities in a given transceiver and then on to a larger scale, a given tactical communication network's overall situation. Each template contains some pre-conditions and post-conditions of an atomic event related to the communication stage along with some security metric(s) information. A successful JCSS simulation will lead to better understanding for a more secure tactical RF communication model. Since we build vulnerability graphs using Bayesian networks (BN), we also assign probability of success after a failure in a pipeline stage's link-edge weight.



Vulnerabilities

precond:

Radio Transmitter:
(Vt1) Receiver Group
(Vt2) Transmission Delay
(Vt3) Link Closure
(Vt4) Channel Match
(Vt5) Transmitter Antenna Gain
(Vt6) Propagation Delay

prostcond:

(Vt1) Receiver Group = 0.99
(Vt2) Transmission Delay = 0.55
(Vt3) Link Closure = 0.65
(Vt4) Channel Match = 0.85
(Vt5) Transmitter Antenna Gain = 0.15
(Vt6) Propagation Delay = 0.25

Figure 3: An example of vulnerabilities template for JCSS and related simulations

Specifying valid probability of communication in different stages requires domain expert knowledge. Most existing vulnerabilities scanning tools report those vulnerabilities with a standard set of categorical security measurements, such as severity level and vulnerability consequences. Therefore, considering the nature of a wireless network, one can define a more than one dimension security or vulnerabilities matrix using these categorical information and quantify levels of each category into numerical values for computation and comparison basis. Our approach is to make each matrix entry value related to each stage in a given transceiver. The result can then be computed and derived by a mathematical function that receives contributions from various dimensions like a normal linear addictive function $f(x + y) = f(x) + f(y)$ or multiplicative function $f(ab) = f(a) f(b)$. Then, it can be converted to a value within range [0,1] by applying a special scalar function. A function of one or more variables whose range is one-dimensional, this scalar function can be applied to the matrix. Such value may be represented the probability of a given vulnerability with respect to the transceiver. For example, One can define a two dimension m × n security matrix W = (wij), with one dimension wi to denote severity levels and another dimension wj to denote ranges of exploits. A 3-scale severity level may be specified as {high = 0.95, medium = 0.65, low = 0.35}, and 2-scale exploit ranges may be specified as {remote = 0.55, local = 0.95}. If applying a multiplicative function to the matrix, then each entry value is given by wij = wi × wj. Our research constructs Bayesian vulnerabilities graphs with our graph generation and mapping routine by matching a list of stages in a given transceiver on a wireless network with profile information against a library of computed vulnerabilities specified node characteristic templates. For any vulnerability, if all pre-conditions are met, values of post-condition attributes are updated with an edge that is assigned with weight. It is then added to the vulnerability graph. The most common task we wish to solve using Bayesian networks (BN) is probabilistic inference. For example, consider the network G with a current vulnerability status W, and suppose we observe the fact that G with a status of W. There are two possible causes for this: either it is due to factor R, or the due to factor S is on. Which is more likely? We can use Bayes' rule to compute the posterior probability of each explanation (where 0==false and 1==true).

$$\Pr(S=1|W=1)=\frac{\Pr(S=1,W=1)}{\Pr(W=1)}=\frac{\sum_{c,r}\Pr(C=c,S=1,R=r,W=1)}{\Pr(W=1)}=0.2781/0.6471=0.430$$

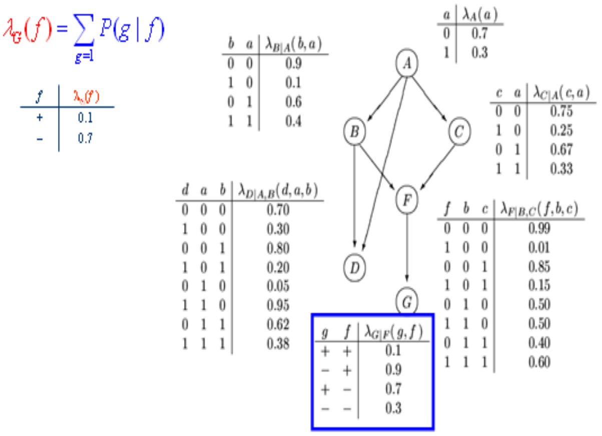
$$\Pr(R=1|W=1)=\frac{\Pr(R=1,W=1)}{\Pr(W=1)}=\frac{\sum_{c,s}\Pr(C=c,S=s,R=1,W=1)}{\Pr(W=1)}=0.4581/0.6471=0.708$$

$$\Pr(W=1)=\sum_{c,r,s}\Pr(C=c,S=s,R=r,W=1)=0.6471$$

where

$$\Pr(W=1)=\sum_{c,r,s}\Pr(C=c,S=s,R=r,W=1)=0.6471$$

is a normalizing constant, equal to the probability (likelihood) of the data. So we see that it is more likely that the network G will have a status of W, because of the weight in factor R is more than factor S: i.e. the likelihood ratio is 0.7079/0.4298 = 1.647. With variable elimination techniques illustrated below and using vulnerabilities graph in figure 4, we use Bayesian networks (BN) with Bucket Elimination Algorithm implementation in the models with belief updating in our scenarios, to the most probable explanation. We need to provide vulnerability values in each communication stage within each transceiver plus the network scores on the entire tactical network. Finding a maximum probability assignment to each and the rest of variables is a challenge. We may really need to maximizing a posteriori hypothesis with given evidence values, finding an assignment to a subset of hypothesis variables that maximize their probability. On the other hand we may need to maximize the expected utility of the problem with given evidence and utility function, finding a subset of decision variables that maximize the expected utility.


$$\lambda_G(f) = \sum_{g=1} P(g \mid f)$$

f	$\lambda_G(f)$
+	0.1
-	0.7

a	$\lambda_A(a)$
0	0.7
1	0.3

b	a	$\lambda_{B\mid A}(b,a)$
0	0	0.9
1	0	0.1
0	1	0.6
1	1	0.4

c	a	$\lambda_{C\mid A}(c,a)$
0	0	0.75
1	0	0.25
0	1	0.67
1	1	0.33

d	a	b	$\lambda_{D\mid A,B}(d,a,b)$
0	0	0	0.70
1	0	0	0.30
0	0	1	0.80
1	0	1	0.20
0	1	0	0.05
1	1	0	0.95
0	1	1	0.62
1	1	1	0.38

f	b	c	$\lambda_{F\mid B,C}(f,b,c)$
0	0	0	0.99
1	0	0	0.01
0	0	1	0.85
1	0	1	0.15
0	1	0	0.50
1	1	0	0.50
0	1	1	0.40
1	1	1	0.60

g	f	$\lambda_{G\mid F}(g,f)$
+	+	0.1
−	+	0.9
+	−	0.7
−	−	0.3

Figure 4: Use of Bucket Elimination Algorithm within vulnerabilities graph

Bucket Elimination Algorithm will be used as a framework for various probabilistic inferences on Bayesian Networks (BN) in the experiment. Finally, a RF Vulnerability Scoring System (RF-VSS) analysis is in development. It is based upon the Common Vulnerability Scoring System [12] and associates with additional features of Bayesian networks [7] (also known as belief network) that in turn yields a more refined belief decision matrix and the matrix can then describes a multiple criteria decision analysis (MCDA) with evidential reasoning approach for vulnerabilities analysis of a given tactical wireless RF network.

IV. EXPERIMENTAL RESULTS

For simplicity in terms of network radio analysis, we provide here a rather simple two (2) nodes wireless RF network scenarios that are communicating with each other via UDP protocol. A more complex one is illustrated in figure 5b. Using some of the available wireless networking analysis toolkits [3] [4] as in figure 5a, a set of JCSS EPLRS Scenarios with a link being jammed. Packets were being captured and exported into Microsoft EXCEL spreadsheet. Jamming occurs between 2 wireless links for this network: EPLRS_6004 and EPLRS_6013. EPLRS_6013 transceiver model was changed to a special EPLRS EW network vulnerability model as in figure 5c. The receiver link was intentionally jammed (by increase the noise level to an extremely high value, i.e. the vulnerabilities within one of the wireless stage are increased by many fold) so that no more simulated packet will be “successful” in getting through from EPLRS_6004 to EPLRS_6013 and the results are listed and illustrated in figure 5d with some sample data.

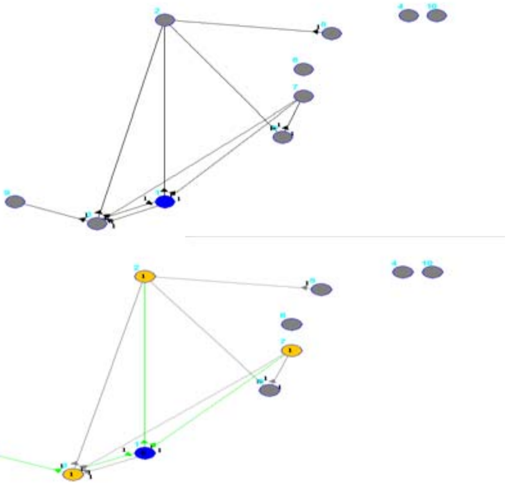


Figure 5a: Wireless networking analysis toolkits in Java

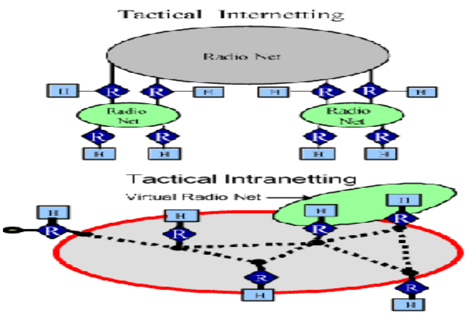


Figure 5b: Wireless RF network

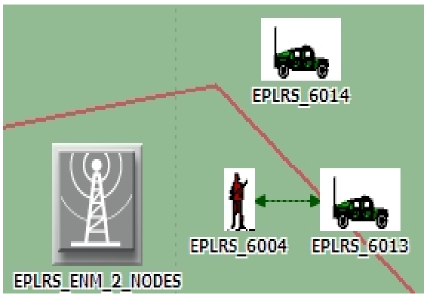
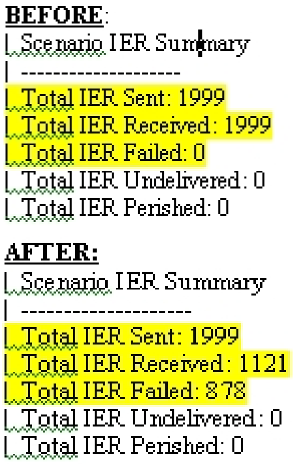


Figure 5c: Two wireless nodes network



```
BEFORE:
| Scenario IER Summary
| --------------------
| Total IER Sent: 1999
| Total IER Received: 1999
| Total IER Failed: 0
| Total IER Undelivered: 0
| Total IER Perished: 0

AFTER:
| Scenario IER Summary
| --------------------
| Total IER Sent: 1999
| Total IER Received: 1121
| Total IER Failed: 878
| Total IER Undelivered: 0
| Total IER Perished: 0
```

Figure 5d: Sample results generated by JCSS scenarios

V. FUTURE DIRECTIONS

Bayesian Analysis [7] – the Bayes' Theorem looks at probability as a measure of a state of knowledge, whereas traditional probability theory looks at the frequency of an event happening. In other words, Bayesian probability looks at past events and prior knowledge and tests the likelihood that an observed outcome came from a specific probability distribution. With some sample field data the Bayes' Theorem can be applied including wireless RF communications & computer networking science in tactical military applications. The research presented here is for building a set of "Bayesian network vulnerabilities graph" for vulnerability study in tactical wireless RF networks. Bayesian network is designed in vulnerabilities graph and model all potential attack steps in a given network. Each wireless network node represents a single security property violation mode; each link edge corresponds to an exploitation of one or more possible vulnerabilities and each network path represents a series of exploits that can signify a potential vulnerability for attack within a tactical RF wireless communication network. Inference is played a major part in our vulnerability calculations. Future research work will involve looking into different kinds of Baysian network (BN) with advanced topological arrangements as in figure 6 below with multiple experts and multiple factors analysis for our more advanced JCSS wireless RF vulnerabilities analysis.

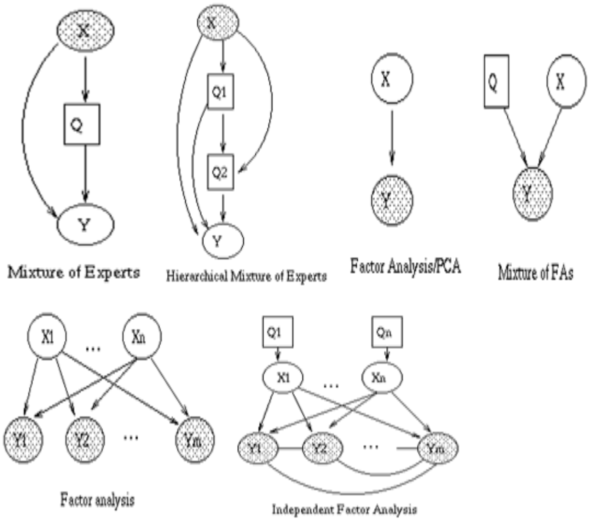
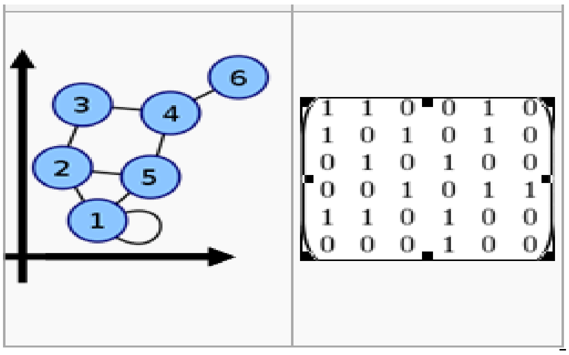


Figure 6: Multiple experts and multiple factors analysis

Finally, we are also proposing an adapted Bayesian network (BN) of wireless tactical network analysis with a RF Vulnerability Scoring System (RF-VSS) that can generate weighted scores in the research. Based upon the Common Vulnerability Scoring System develops by Peter Mell et al. [12], we think this is a very valuable, useful tool and scoring system for quickly assessing wireless RF security and vulnerabilities. RF-VSS scores are derived from three scores: a "base network" score, an "adversaries impact" score, and an "environmental impact" score. These can better be described as "fixed" score, "external variable" score, and "wireless RF network experts" assigned score. The base network system score is fixed at the time the vulnerability is found and its properties do not change. The base assigned score includes numerous scoring metrics. Each of these metrics will then be chosen from a pre-determined list of options. Each option has a value. The values are then fed into a formula to produce the base network score. Next comes the temporal or adversaries impact score. The adversaries impact score changes and revises the base network score up or down. The temporal or adversaries impact score can also change over time (thus it is "time sensitive"). For example, one of the component metrics of the adversaries impact score is System Remediation Level (SRL). This means, there exists a possible common defense fixes out there, maybe from a contractor or vendor or an emergency research workaround. If, when the detected vulnerability is first encountered, there may be no possible fix, then the temporal or adversaries impact score will be much higher. But when a solution or fix is possible, then the score will go down dramatically. Again, it was temporary and a changing factor. There are three possible vulnerabilities metrics that make up the temporal or adversaries impact score. This score is then multiplied by the base network score to produce a new score. This first computed new score will be produced based upon the current operating wireless RF network scenarios set up via background expert diagnostic. The final part is the environmental impact score. This is how the final vulnerability will affect the wireless RF network. The researchers get to determine how the combined vulnerabilities might affect the overall wireless RF network in field deployment. If the vulnerability has very little risk or to do with all the listed factors then this computed score will be very, very low (like zero). There are five metrics that affect the environmental impact score. This portion is combined with the base network and temporal adversaries impact score to produce a final score. The score will be on a scale of 1-10. If it is a low 2, then don't be too worried. However, a rather higher score like 6 or above might indicate major security issues in terms of security. We will provide a vulnerabilities smart index by constructing a novel calculator with a set of RF Vulnerability Scoring System (RF-VSS) for final system vulnerability analysis. For an example: For a given wireless RF radio network, according to expert released analysis and advisory, there are a set of “RF wireless network vulnerabilities" being assigned. The example metrics for the given wireless RF network scenarios with vulnerabilities are: (1) base network impact, (2) temporal or adversaries’ impact and (3) Environmental impact. So, overall a base RF wireless network vulnerability score of 8.8 (very bad) that is slightly mitigated to 7.9 by the temporal or adversaries metrics. Still, 7.9 is not a great score and still has considerable amount of risk. Now, this is where the final environmental impact score comes in to alter the landscape. The negative impact may be bad for the overall wireless RF network when we look at the environmental impact metrics calculated before for certain wireless network scenarios as illustrated above. We gather all those factors into the RF Vulnerability Scoring System (RF-VSS) calculator and it produces an environmental score of 6.5 which translates into high vulnerabilities. This is a relatively good approach to determine what the overall risk is for a give wireless RF network and the RF Vulnerability Scoring System (RF-VSS) analysis is based upon the Common Vulnerability Scoring System develops by Peter Mell [12] and associates with additional features of Bayesian networks [7] (also known as belief network).

VI. CONCLUSIONS

Bayesian networks [7] can be used as a powerful tool for calculating security metrics regarding information system networks. The use of our Bayesian network model with the mechanisms from CVSS is in our opinion an effective and sound methodology contributing towards improving the research into the development of security metrics by constructing a novel calculator with a set of RF Vulnerability Scoring System (RF-VSS) for final system vulnerability analysis. We will continue to refine our approach using more dynamic Bayesian Networks to encompass the temporal domain measurements established in the CVSS. This short paper demonstrated an approach to model all potential vulnerabilities in a given tactical RF network with Bayesian graphical model. In addition, using a modified belief decision matrix, the research can describe a multiple criteria decision analysis (MCDA) using Evidential Reasoning Approach. With evidential reasoning approach, a generic evidence-based multi-criteria decision analysis (MCDA) approach is chosen for dealing with problems having both quantitative and qualitative criteria with variables. This matrix may be used to support various decision analysis, assessment and evaluation activities such as wireless RF networks environmental impact assessment and wireless RF networks internal nodes (transceiver) assessment based on a range of quality models that are developed. Bayesian vulnerabilities graphs provide comprehensive graphical representations with conventional spanning tree structures. The Bayesian vulnerabilities graph model is implemented in Java, and it is deployed along with JCSS software. JCSS is the Joint Net-Centric Modeling & Simulation Tool used to assess end-to-end communication network capabilities and performance. It is the Joint Chiefs of Staff standard for modeling military communications systems. JCSS is a desktop software application that provides modeling and simulation capabilities for measuring and assessing the information flow through the strategic, operational, and tactical military communications networks. Our new tool can generate implement vulnerabilities network graph with link edges and weights. All these may be transposed into an adjacency-matrix as illustrated below for a more quantitative wireless RF network vulnerability assessment. The convention followed here is that an adjacent edge counts 1 in the matrix for an undirected graph as in figure 7. (For example a given X, Y coordinates that are numbered below from #1 to #6 may be transposed into a 6x6 matrix.)



$$\begin{pmatrix} 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

Figure 7: Transpose the vulnerabilities graph into a matrix

The vulnerabilities analysis of a wireless RF network is then achieved by assigning corresponding measurement metrics with posterior conditional probabilities of Bayesian network [7]. The Bucket Elimination algorithm is adapted and modified for probabilistic inference in our approach. The most common approximate inference algorithms are stochastic MCMC simulation, bucket algorithm and related elimination steps which generalizes looping and aggregated belief propagation, and variation methods. A better approximate inference mechanism may be deployed in the near future for more complex vulnerabilities graph. Our method is very applicable to tactical wireless RF networks by picking, implementing each model's communication stages and states. The result when using with OPNET JCSS [2] simulation and modeling will provide both graphical quantitative and real assessment of RF network vulnerabilities at a network topology state and during time of actual deployment.

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