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AN EXAMINATION OF THE SECURITY IMPLICATIONS OF THE SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA) SYSTEM IN A MOBILE NETWORKED ENVIRONMENT: AN AUGMENTED VULNERABILITY TREE APPROACH.

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Abstract The increasing demand of supervisory control systems connected remotely to critical infrastructure and recently the internet, has profiled a high threat level to the security and function of control system; more especially Supervisory Control and Data Acquisition (SCADA) systems. It is very crucial that operators and management are knowledgeable about these threats and get familiarize with ways to trace and track information required mitigating the threats. In present day very competitive markets and with high levels of infrastructural investments, it is of vital importance for corporations to be up-to-date with their SCADA networks so as to meet the challenges faced by remote and/or mobile access, use and cyber threat posed to the critical systems infrastructures. We have examined the security implications of having the SCADA system exposed to the mobile and/or internet environment. The paper deals with the following issues: Section one looks at types of infrastructures and the general functionalities of SCADA and assesses the risks in mobile environment. The second section employs some of the recent methodologies applied to the SCADA system. Section three reports on some findings from analysis and critically evaluates the risks posed to the system using an augmented vulnerability tree approach. The last section draws from the findings to re-evaluate, conclude and proposes some solutions on the risk issues of operating SCADA in a mobile networked environment.

Keywords: Supervisory control and data acquisition (SCADA) system, Industrial automation, monitoring and Control, automation application, security, risk assessment, network system vulnerability, mobile and Internet environment.

1. Introduction

Critical Infrastructure is used to best describe assets that are vitally important for the functioning of a system – organization, society and economy. Most computing, engineering, manufacturing and controls

systems are categorized as critical infrastructures as their exploitation may jeopardize continuity of business operations, the environment, security and regulatory oversight, corporate liability, human health and safety, and stakeholder perceptions. Supervisory control and data acquisition

(SCADA) systems are crucial to the safe and efficient operation of many critical infrastructure components which are in wide use today and applicable to many different industry sectors. The system monitors and control industrial systems in areas such as Oil and Gas, Air traffic and Railways, Power generation and transmission, IT, Computational processing, Water management, Manufacturing Production plants, and many more.

The general functionality of SCADA systems involves receiving field-data collected by remote terminal units (RTUs) and controlling physical devices such as switches and pumps by using RTUs. The master computers (MTUs) provide the information such as meter readings and equipment status to human operators in a presentable form and allow the human operators to control the field equipments or control devices automatically. The MTU initiates almost all communication with remote sites. Many early SCADA systems used mainframe computer technology making them hierarchical and centralized in nature and required human oversight to make decisions. SCADA systems were developed for gathering data from long distances using poor communication systems but providing high levels of reliability and operability. MTUs were specialized, dedicated computers which gathered information and sent control command over 1200-baud communication lines to RTUs with no local intelligence or function beyond serving the master station. Very little change occurred in SCADA system concepts during the first 30 year of the industry (Sciacca, S.C et., al Jan. 1995), The recent advances in the communication technologies and media (fiber optics, direct satellite broadcast and so forth), and

increased processing power available at substation freed the SCADA architecture and functionality from the archaic 100-baud limitation of the past communication systems.

1.1. Risk tools and methodologies

It is mandatory that all devices on our critical infrastructure have to be protected and the threat associated to them have to be identified. After which, the procedure and policy will follow, and the technology that is required for protecting them can be implemented. Risk assessment is generally a vast area, which involves different approaches and there are many tools for assessing the risk in various situations such as, in a mobile networked environment.

Assessing the risk to critical infrastructures can be looked at from different approaches, for example; the Operational Critical Threat, Asset, and Vulnerability Evaluation (OCTAVE) (Alberts, et al., 2003), which is a framework for identifying and managing information-security risks. CORAS (Aagedal et al., 2002) is a tool-supported methodology for model-based risk analysis of security-critical systems. A Sandia National Laboratories report (Campbell & Stamp, 2004) attempts to classify risk assessment methods, according to the level of detail and approach in order for users to be able to select the most appropriate method to use. The Leontief Input–Output models (Rinaldi, 2004) provide an aggregated, time-independent analysis of generation, flow, and consumption of commodities among infrastructure sectors. Such modeling and simulation abilities are integral to infrastructure risk analyses. Haimes, et al., (2002) describe a Risk Filtering, Ranking, and Management

(RFRM) method, which builds on the hierarchical holographic model (HHM) (Haimes & Chittester, 2005) to identify risks, but then filters and ranks the risks so that the risks can be addressed in the order of priority. Haimes and Chittester (2005) also use Inoperability Input–Output Modeling (IIM) to quantify economic losses and their propagation through the various economic sectors for large-scale civil infrastructures controlled by SCADA systems over internet protocol communication networks. Meanwhile (Nozick et al., (2005)) looked at representing interdependent infrastructure networks using Markov and semi-Markov processes to reflect uncertain capacity on network links. However, none of these methods deals with assessing the risk of SCADA in a mobile networked environment

1.1.1 Other methodologies

Recent methodologies by Stoneburner (2006), proposes the unified risk framework that provides a common language for risk management that may be used for describing risks. Quantitative risk analysis methods fall under the broad category of probabilistic risk assessment (PRA). A generally accepted definition of PRA is a systematic and comprehensive methodology to evaluate risks associated with a complex engineered technological entity. Although PRA technically includes a risk identification phase, it does not provide the guidance of methods like HHM, but rather assumes that the designer can identify the risks. PRA includes all fault/attack tree analyses (FTA), attack tree analysis (Schneier, 1999), event tree analysis (ETA), Vulnerability Tree Analysis (VTA) (Vidalis & Jones, 2003), failure mode and effect analysis (FMEA), or failure mode effect and criticality analysis (FMECA) (Ayyub, 2003); and

cause/consequence analysis (CCA) (Pumfrey, 1999), as well as methods that use directed graphs and logic diagrams (Henley & Kumamoto, 1996). Most other methods are extensions or combinations of these. Many of the tools mentioned earlier incorporate these methods to varying degrees. To perform the fundamental security analysis of computer-based information systems, one is tempted to use Dijkstra's weakest precondition approach. In fact, Yasinsac and Childs (2001) have done some initial work in this direction for general Internet security, which can be applied to information management systems.

2. Effect of SCADA Systems

Recent developments in Information and communication technologies have fueled the pushed for mobile SCADA systems within corporate IT infrastructure. This mobile devices technology presents a unique set of problems for a networked based SCADA system that need to be carefully addressed, and in fact more recent studies (Alex W. Dan E., 2008) have tried to examine how SCADA systems can optimally be operated over GPRS networks

2.1 Associated Wireless Technologies

Some widely used wireless media for SCADA are: private wireless networks (analog or digital), dedicated wireless Multiple Address Systems (MAS), specialized public digital radio networks such as TETRA, iDEN or ASTRO (APCO-25), Broadband Networks and public cellular services such as the Global System for Mobile communications (GSM) and General Packet Radio Service (GPRS) and

Internet, providing Internet Protocol (IP) service.

The GPRS is a packet data switched technology, using the same Infrastructure as the GSM network. The intention for developing the GPRS technology was to provide broadband access “on the move”, similar to the wired Internet service which uses circuit switched ISDN, ADSL, or coaxial cables. Using GPRS, network resources are instantly available when data (message) actually needs to be transmitted across the wireless media. The transmitted data is divided into packets prior to being sent via the wireless modem. Common data applications over GPRS include file transfer, pictures, video, Voice over IP, and the ability to remotely access and control industrial installations.

The GPRS network offers data rates up to of 150 kbps, depending on network availability, channel coding scheme, and data terminal capability. This increase in data transmission rates with respect to GSM (circuit switching method) is achieved by using more than one timeslot of the TDMA frame. However each operator can assign one or more time slots. GSM/GPRS networks operate in four RF bands: 850/1900 MHz (USA and Latin America) and 900/1800 MHz (Europe, Africa, Asia, Middle East, and Latin America). GPRS modems manufactured today, like the Motorola g-24, operate in all four ranges (quad-band)

Naturally, not all GPRS based communications are identical. Simple SCADA devices like standard RTUs or standard PLCs can communicate over GPRS networks using advanced type GPRS modems with embedded IP stack and having a PC based server. The network in this case is similar to a fixed server-to-mobile cellular

subscriber communication rather than being optimized for SCADA.

2.1.1 SCADA wireless network performance issues.

When a SCADA system is used over a public GSM/GPRS network, users should set realistic expectations and must remember that there is a compromise between cost and performance, since the operating parameters relating to data traffic are affected by the following factors:

- Network loading - this might be uncontrollable and unpredictable with a tendency to sudden increase during emergencies (weather conditions, earthquake, terror event, etc.).
- Re-establishment - a disconnected IP link might take up to 10 seconds, depending on network loading. This delay might create a problem for time-critical SCADA applications.
- Data loss - overloaded networks often cause messages to get lost in transit and no confirmation sent to the sender. These events might in turn trigger additional traffic and result in even more delays due to resending of messages, errors or poorly performing SCADA system.
- Network crash or downtime - while operators are doing their best to ensure good Quality-of-Service (QoS), the GPRS remains a public network and is not a fault-proof system. It might crash due to attack; overload etc. and the service to parts of the network/areas can be interrupted for an extended period.
- In principle, SCADA users on GPRS networks have no priority over regular cell phone users' subscribers.

In some instances, and depending on the revenue scheme of the operator, other data users (video, news download, games

players, etc.) may even be given a higher priority access than SCADA users.

3.0 An Augmented Vulnerability Tree Approach Model.

The Augmented Vulnerability Tree Approach (AVTA) is a proposed new methodology, that combines the concepts of vulnerability tree analysis (Vidalis & Jones, 2003), fault tree analysis (Ayyub, 2003), attack tree analysis (Schneier, 1999), and the cause–consequence technology (Pumfrey, 1999); to produce what is believed to be a more effective risk analysis model.

Most, if not all of the tree-analysis methods are very similar, but they differ primarily in what defines the top event. For example, the fault tree/attack tree/vulnerability tree method is a deductive process, where, the topmost undesirable event is first postulated. Afterwards, the ways for this event to happen are deduced. The deduction process results in a tree that includes all failure components that could contribute in causing the top event. Therefore a vulnerability tree is a logical model representing the logic of system failures qualitatively. A tree diagram is often constructed as a graphical illustration showing the stepwise cause resolution using formal logic symbols.

In some instances, and depending on the revenue scheme of the operator, other data users (video, news download, games players, etc.) may even be given a higher priority access than SCADA users.

3.1 The Steps

In constructing the Augmented Vulnerability Tree Approach (AVTA), we have come up with the following steps:

Step 1: Construct the base-level and expanded vulnerability trees

To construct a vulnerability tree, the top undesirable event is first postulated which represents a pivotal event for a particular failure scenario. The possible means (attacks) for this event to occur are systematically deduced. These attack paths can result in a failure (the top event). Then, each situation (base-events) that could cause an attack is added to the tree as a series of logical expressions. Thus, the intermediate failure events (“attacks”) are connected to the top event and basic events with logic gates, the most common of which are “AND” gates and “OR” gates. In a vulnerability tree, the AND gate is used when all the base-events connected by this gate must happen to launch an attack. The OR gate is used when any one of the base-events connected by this gate is sufficient for an intruder to launch an attack.

Step 2: Construct effect analysis table and calculate threat-impact

From the vulnerability tree a list of all threat types is created. Each of these threats is considered one at a time and a list of various effects, or types of damage, is constructed. Using these effects, a table showing effects for each attack is created. Then, using the attack history/logs, the frequency of attacks is calculated. A damage/impact dollar value for each event is calculated by interviewing the operators, engineers, accountants, and managers. The probabilities and the impacts (listed in dollar amount) are normalized so that the values range from 0 to 100. The probability of each attack is multiplied by the total maximum damage amount caused by the attack.

Step 3: Add threat-impact index values to vulnerability tree

The threat-impact values from the effect analysis table are marked on the vulnerability tree. The top event of a system without any implemented security (base vulnerability tree) will have the threat impact index of 100. After security enhancements are applied, this value is expected to be reduced in the new vulnerability tree.

Step 4: Calculate the vulnerability index values

The cyber-vulnerability indices are assigned to all the base-events by using the threat-impact index of their parent event in a vulnerability tree. The threat-impact index is equally divided among all the base-events at the same level. AND and OR are treated the same way while dividing the parent-level values. Once all the base-events have the cyber-vulnerability indices assigned to them, the cyber-vulnerability index for the attack tree is calculated by summing up all the cyber-vulnerability indices.

Step 5: Complete augmented vulnerability tree by adding vulnerability index values

The expanded tree now has graphical information about threats, the impact of these threats, and the vulnerability of the system to electronically launched attacks.

Step 6: Repeat steps 2 to 5 for proposed security enhancements

Security enhancement should lead to lower threat impact index and cyber-vulnerability index values. However, some security enhancements may not result in lower values if other vulnerabilities continue to enable a threat.

4. Case study

This section describes the configuration for the SCADA test bed at the University of Louisville and illustrates how the proposed method was applied to the system component that performs information communication. The method is also illustrated on the same component after two security enhancements were applied to the protocols used for information communication

4.1 Vulnerabilities Analysis of SCADA in a mobile networked environment

The research objective of the SCADA test bed at the Intelligent Systems Research and Chemical Engineering Laboratories at the University of Louisville is to evaluate operation of a SCADA system under carefully monitored and safe operating conditions. The specific control objective is to regulate the fluid level in a multiple tank and pump system through supervisory control. Details on the process operation are available online (Patel, et al., 2005). The communication component of this test bed sends the control data entered by engineers to a remote terminal unit (RTU) and sends real-time parameter values from the RTU to the master terminal unit (MTU). These message exchanges are done via software programs, written in Java, and use a subset of the Distributed Network Protocol version 3 specifications. The component uses a client-server architecture where the MTU acts as a client and the RTU acts as a server. The server waits for any requests, such as writing to a file, from the client. The details of the architecture have been presented (Patel, 2006; Patel, et al., 2005).

4.2 Critical Analysis and Evaluation

STEP 1: Create the base level on vulnerability tree

There is general attack against mobile network communication system which is outlined in the tree that can be instituted against Remote terminal unit and master terminal unit. Hence, the attacks are the base event for the RTU and MTU. Any attack that is launched against the MTU is a specific attack. The attack is then classified into three categories in the proposed approach: Mobile attacks among the master and the slave, attacks against the master and the slave, the possibility of an attack against the MTU necessitate an attacker attempting to trick the MTU by manipulating a control message. There are possibly Similar attacks against the RTU is classified as the response alteration to the RTU.

The possibility of an attacks on a mobile network systems can be classified as an attacker trying to resend manipulated message (replay attack) it, spoofing attempt to send a fake message, (DOS attack). Eavesdropping attacks (unauthorized interception of information in transit through the use of methods other than wiretapping), and gaining information by sniffing or tapping a line between two unsuspecting parties traffic analysis (intercepting and examining messages to deduce information from patterns in communication), are included in the augmented vulnerability tree structure attacks are in passive forms and they have direct impact on mobile SCADA security.

The tree below shows the base events that include the flaws such as nonce not included in the response. A message transmitted from a remote terminal unit in reference to a requested message from an MTU is called a response. The Mark in one of the base events is a value that is diverse every time a

message is sent is called a nonce. Message that is readable in its normal text, which every system can read as opposed to encryption, is called a Plaintext.

An MTU sends petition in a readable text which is outstanding as the base events, which means that the entire information is transmitted in a readable form. The origin authentication refers to a countermeasure modeled to form the validity of the originator of information. A session is a form of connection among an MTU and an RTU. A countermeasure that is modelled to form the validity of the content of the information is referred to as authentication. A security countermeasure that proves the uniqueness of the person who attempts to use the system is called an access authentication.

STEP 2: Calculate threat-impact values and create the damage analysis table

Table 1 below is listed as a row in the damage analysis table which is the attacks. To generate columns, show a list all the possible loss that have been produced from the result of each attack. The duplicates are then removed and the losses are put in groups. In table 2, the first eight columns show the outcome from the loss. The financial loss caused while attempting to run the operation without the full use of the SCADA control system is the loss of control or scene.

For the operation to be run manually it will require an extra hour cost for the operator.

The operation breakdown costs and material lost is referred to as Loss of production. The loss outcome from idle personnel; which is computed by multiplying the number of personnel, their idle hours, and their salary per hour, is referred to as Loss of staff time. The amount of loss done to the operation equipment is referred to as Equipment loss. Fixing software problems and operations

equipments is included in the cost of remedying intrusion.

Table 3 (see appendix) gives a summary of the attack tree diagram. This is a complex tree because mobile SCADA is a complex program.

Denial of service	Flood network, disrupt a connection between one or more device
Control message modification	Seize and change control information
Replay	Seize information and send it back later
Spoofing	fake to be an RTU or MTU
Write to RTU	Change or Add data on MTU
Write to MTU	change response and transmit to MTU
RTU response alteration	Change and Add values on RTU

Table 1: Threat Classification

	Loss of control (\$)	Loss of production (\$)	Loss of staff time (operation salary)				Equipment loss (\$)	Cost of remedying intrusion people cost \$	Total loss (\$)	Prob.	Normalized loss (previous -value / previous column) total %
			# Op	# Hours (h)	Pay/h (\$)	Total (\$)					
Replay	1,000	15,000	1	40	35	1,400	0.00	20,000	37,400	0.20	8.00
Spoofing	4,000	100,000	1	80	35	2,800	25,000	35,000	166,800	0.05	9.00
Denial of service	6,000	100,000	2	50	35	3,500	5,000	15,000	129,500	0.20	27.00
Control message modification	4,000	400,000	5	120	35	21,000	75,000	50,000	550,000	0.05	29.00
Write to MTU	0.00	20,000	1	40	35	1,400	25,000	20,000	66,400	0.20	14.00
RTU-response alteration	1,000	15,000	1	40	35	1,400	0.00	10,000	27,400	0.10	3.00
Write to RTU		20,000	1	40	35	1,400	5,000	20,000	46,400	0.20	10.00
Total		0	0				0	0	0	1.00	100.00

Table 2: Damage analysis Table

Attacker Goal	Technical Difficulty	Severity of Impact	Problem of Detection	Underlying Critical Vulnerabilities	Comments
Gain SCADA system access	1- 4	Very low	Low	<ul style="list-style-type: none"> • Wireless devices • SCADA transmission media • Remote field sites • 3rd party access 	<ul style="list-style-type: none"> • Difficulty highly dependent on point of access and security measures in place • Goal for all other critical precursor
Identify RTU or MTU device	2	Very low	Low	<ul style="list-style-type: none"> • No confidentiality 	<ul style="list-style-type: none"> • Goal for all other critical precursor
Disrupt master slave communications	2	Moderate	High	<ul style="list-style-type: none"> • No authentication • No session structure • Simplistic framing tech. 	
Disable slave	2	Moderate	High	<ul style="list-style-type: none"> • No authentication • No session structure • Simplistic framing tech. 	
Read data from slave	3	Moderate	Very low	<ul style="list-style-type: none"> • No confidentiality • No authentication 	
Write data to slave	3	High	Very low	<ul style="list-style-type: none"> • No authentication • No session structure • No integrity 	
Program slave	3	High	Low	<ul style="list-style-type: none"> • No authentication • No session structure • No integrity 	
Compromise slave	3	Very high	Low	<ul style="list-style-type: none"> • No of integrity • No authentication 	
Disable master	2	Moderate	High	<ul style="list-style-type: none"> • No authentication • No session structure 	
Write data to master	3	High	Low	<ul style="list-style-type: none"> • No authentication • No session 	

Attacker Goal	Technical Difficulty	Severity of Impact	Problem of Detection	Underlying Critical Vulnerabilities	Comments
				structure	
Compromise master	4	Extreme	Low	<ul style="list-style-type: none"> No authentication No session structure 	<ul style="list-style-type: none"> Very useful precursor to other attack

Table 3: Summary of the attack tree

To compute the dollar amount the average loss values are used. Different means are used to compute loss orderly. First, Case studies and other literature on critical-system attacks were studied. Specifically, the loss was estimated using the data in (Rakaczky, 2005). For those who are interested in using a large volume of data on losses, Its recommended for them to use the British Columbia Institute of Technology Industrial Security Incident Database (Byres and Lowes, 2004), which provides one of the most Comprehensive event databases record on cyber-attack for critical infrastructures.

Next, used the outcome from the enhanced SCADA to find a typical range of loss they encountered. Using the data from the case study, the costs of different devices of the SCADA case study where considered, and finally I created the attack tree above with their counter measures I used the same process to get the estimate for the probabilities.

Step 3: Addition of threat impact value to tree for enhancement

The threat-impact index value on the attack tree is shown in the last column of the damage analysis table. They are marked on the augmented vulnerability tree .the values add up to a total amount of 71 in the tree since there is no security enhancement yet.

Step 4: calculate the mobile vulnerability index values

The threat-impact index of each attack is now subdivided equally among the base events. As shown in Fig. B, a threat-impact index of 27 for the denial of service attack is divided equally into two of its base events, with each event having an index of 13.5.

Similarly, since the control-message modification attack has three events, one third of this attack's threat-impact index value is assigned to each of its base events. As noted earlier, we assume a simple, un-weighted distribution, and divide the index equally among base events. Therefore, the threat-impact index for the replay attack is divided into two at the first level, giving the MV index of 4 to the base events of no-origin authentication. The other two events are at a lower level and hence each of these base events is assigned the MV index of 2.

Step 5: add vulnerability index value to tree and complete the tree

In the augmented vulnerability tree, the high event is presents with MV index value of a system. The index, which is 71, makes up the total MV indices of all the base events scheduled above. The corresponding base Event could be scheduled below more than one attack. Shown in the illustration is the completed augmented vulnerability Tree, the Threat-impact indices are marked as TI

indices and the Mobile-Vulnerability indices are marked as MV indices.

5. Case study explanation

- Nonce not included in response: one base event with a MV index of 1.
- Response sent in plaintext: one base event with a MV index of 1 and another base event with a MV index of 1, giving a total of 2.
- Nonce not included in request: one base event with a MV index of 1.
- MTU sends request in plaintext: one base event with a MV index of 1 and another with 9.67, giving a total of 10.67.
- No-origin authentication by RTU: one base event with a MV index of 4.5, one with 2, one with 13.5, one with a MV index of 9.67, and one with a MV index of 5, giving a total of 34.67.
- No-origin authentication by MTU: one base event with a MV index of 4.5, one with 2, one with 1, and one with 7, giving a total of 14.5.
- Session open after unsuccessful tries: one base event with a MV index of 13.5.
- No-content authentication by RTU: one base event with a MV index of 9.66.
- No access authentication by MTU: one base event with a MV index of 7
- No-access authentication by RTU: one base event with a MV index of 5.
- No-content authentication by MTU: one base event with a MV index of 1.

The complete augmented vulnerability tree is shown in Fig. 1 in the appendix. The mobile vulnerability indices are marked as MV indices and the threat-impact indices are marked as TI indices.

6. Proposed solution on mitigating the risk issues of operating SCADA in a mobile networked environment.

Two SCADA communication security enhancements have been suggested (Patel, 2006) and implemented on the test bed described above. The proposed enhancements include the Authentication Octets and Challenge–response authentications. The Authentication Octet enhancement is based on the digital-signature algorithm. In this enhancement, additional bytes of information, referred to here as Authentication Octets, are appended to each message from an MTU to an RTU for authentication. First, the MTU performs hash on the selected bytes of the message it intends to send; which results in generating a hash digest. The MTU encrypts this digest by using its private key and then the MTU sends the encrypted digest along with the message. The message itself is not encrypted to save processing time duration.

7. Conclusion

This paper has discussed a number of important real-life issues in the security of SCADA systems in a mobile networked environment that controls much of the critical infrastructure around the world. Many of the current vulnerabilities in these systems are either due to the inadequate security measures or no security in the SCADA network, whether directly or indirectly, through the public Network. This paper attempts to provide two significant resources for systems engineers who now struggle to cope with the worsening and very

challenging security situations. The paper looks at the types of infrastructures and the general functionalities of SCADA and assesses the risks in mobile environment. It employs some of the recent methodologies as applied to the SCADA system. The paper also reports on some findings from the detail analysis and critically evaluates the risks posed to the system using an augmented vulnerability tree approach. The last section draws from the findings to re-evaluate, conclude and proposes some solutions on mitigating the risk issues of operating SCADA in a mobile networked environment.

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Appendix: Figure 1

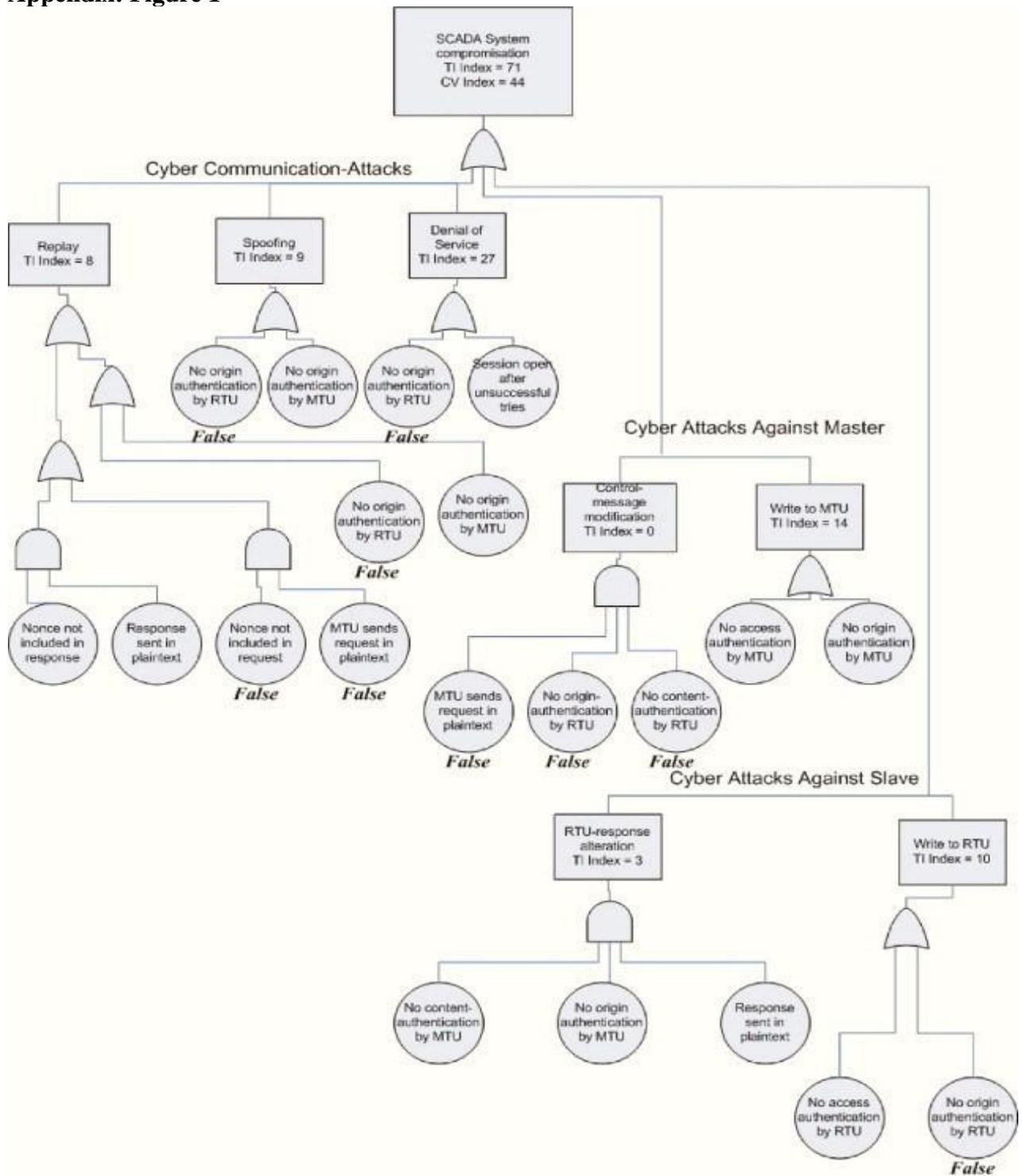


Figure 2:

