Practical Modbus Flooding Attack and Detection

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Abstract

The Modicon Communication Bus (Modbus) protocol is one of the most commonly used protocols in industrial control systems. Modbus was not designed to provide security. This paper confirms that the Modbus protocol is vulnerable to flooding attacks. These attacks involve injection of commands that result in disrupting the normal operation of the control system. This paper describes a set of experiments that shows that an anomaly-based change detection algorithm and signature-based Snort threshold module are capable of detecting Modbus flooding attacks. In comparing these intrusion detection techniques, we find that the signature-based detection requires a carefully selected threshold value, and that the anomaly-based change detection algorithm may have a short delay before detecting the attacks depending on the parameters used. In addition, we also generate a network traffic dataset of flooding attacks on the Modbus control system protocol.

Keywords: Modbus, Denial-of-Service (DoS), Change Detection, Intrusion Detection

1 Introduction

Supervisory Control and Data Acquisition (SCADA) systems are used in many industrial sites to remotely monitor and activate motors, pumps and other equipment that run water processing plants, factories, refineries and electricity substations.

In recent years control systems have been upgraded from the standard serial bus systems to modern Transmission Control Protocol (TCP)/Internet Protocol (IP) based systems. This has resulted in cost savings as standard Information and Communications Technology (ICT) Ethernet cabling can be used, but it has also provided the convenience of allowing these control systems to be connected to existing data networks. The trade off in this course of action, that is connecting these control systems to the Internet exposes them to existing cyber attacks. Traditionally, control system devices and protocols have not been designed to withstand malicious attacks. It is important to determine how vulnerable these systems are and how to detect if an attack is being conducted on these systems so that appropriate action can be taken before serious damage occurs.

The published work regarding vulnerabilities and attacks on industrial control systems is growing (Huitsing et al. 2008, Morris et al. 2013). However, to the best of our knowledge, there is currently no work in the public domain that practically demonstrates such attacks and their detection. This paper concentrates on the common Modicon Communication Bus (Modbus) control protocol that has been adapted to run over TCP/IP. It has not been designed to provide any security properties, therefore it is vulnerable to many types of attack. This paper focuses on flooding attacks as they are the easiest attack to conduct on a SCADA system. The work also explores different detection techniques that can be used to identify when an attack is being conducted. The contribution of this paper is two-fold. Firstly, we show that it is possible to use flooding attacks to successfully subvert a control system using Modbus. Secondly, we show that the anomaly-based change detection algorithm and the signature-based Snort threshold module are capable of detecting a Modbus flooding attack. Additionally, we also provide a set of experiments that results in a network traffic dataset of flooding attacks on the Modbus control system protocol. These datasets can be used to validate a variety of intrusion detection algorithms.

This paper is divided into seven sections. Section 1 introduces the paper and gives a brief description of the existing Modbus over TCP protocol. Section 2 reviews related work on Modbus vulnerabilities and attack detection. Section 3 describes the flooding attack and the software that was developed to successfully conducted the attack on our experimental system. Section 4 introduces the theory behind the two intrusion detection mechanisms that are used to detect the flooding attacks. Section 5 describes the experimental methodologies used to generate a range of datasets that we present and analyse in Section 6. Section 7 concludes the paper.

1.1 Modbus

Devices connected using the Modbus protocol communicate with each other using a master-slave or server-client configuration (Modbus Organization Inc. 2006). The master device controls all the activities such as the transmission and monitoring. It initiates the queries while the connected devices or slaves, respond to the queries. For this reason, the Modbus protocol is referred to as a single master protocol. The

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MODBUS Application Protocol (MBAP) Header				Protocol Data Unit (PDU)	
Transaction Identifier	Protocol Identifier	Length Field	Unit ID	Func Code	Func Data (variable length)

Figure 1: Modbus/TCP ADU Message Structure

master device can either send a broadcast message to all connected and configured slave devices, or poll a slave device individually (Modbus Organization Inc. 2006).

Modbus packets also have function codes which specify the type of operation requested. Every Modbus device has a register map of functions that are used to monitor, configure and control module input/output. There are two main variants of Modbus protocol, Modbus Serial and Modbus/TCP. For this paper, we will focus on Modbus/TCP, and for the remainder of this paper references to Modbus mean Modbus/TCP.

Modbus is a communication protocol designed to allow communication of industrial equipment such as computers, sensors, Programmable Logic Controllers (PLCs) and other physical input/output devices over the IP/Ethernet network. TCP/IP and Ethernet are used in carrying Modbus message structure. Modbus is a protocol embedded inside the TCP/IP frames of Ethernet (Modbus Organization Inc. 2006). Figure 1 depicts the structure of a Modbus IP Message known as Modbus Application Data Unit (ADU).

The message structure of Modbus ADU is shown in Figure 1, and is divided into two parts (Morris et al. 2013). The first, is the Modbus Application Protocol (MBAP) Header, which consists of:

1. Transaction Identifier (2 bytes) - Used for synchronisation between server and client messages.
2. Protocol Identifier (2 bytes) - Set to 0 for Modbus, for potential future use.
3. Length Field (2 bytes) - Used to define the number of remaining bytes in this message structure.
4. Unit Identifier (1 byte) - Slave address of device the message structure is to be sent to. For Modbus, address of slave device is the IP address and therefore the Unit Identifier is set to 0xFF.

The second part of a Modbus ADU message is a typical Modbus Protocol Data Unit (PDU) message. It consists of:

1. Function Code (1 Byte) - Modbus supported functions.
2. Function Data (n bytes) - Data accompanying the Function Code as a response or command.

2 Related Work

This section provides an overview of previous work undertaken on Modbus, and Intrusion Detection System (IDS) for Modbus protocols. The Modbus protocol provides no security for messages. Messages are passed in the clear providing no confidentiality, or message integrity (Modbus Organization Inc. 2006).

Huitsing et al. (Huitsing et al. 2008) provides a compilation of attack taxonomy on the Modbus protocol, with the analysis focusing on Modbus serial and TCP protocols. According to the research, the corresponding targets include the master, field device slaves, network communication links and messages. Huitsing et al. outlines that Modbus attacks consist of protocol specification attacks, which are common to all Modbus implementations. A total of 28 attacks were identified for Modbus protocols. Some of these attacks include spoofing, Modbus network scanning, baseline response replay, and direct slave control. Modbus flooding attack was not included in the list of attacks presented in Huitsing et al.. Furthermore, the paper does not discuss any practical analysis of the attacks.

Queiroz et al. (Queiroz et al. 2009) conducted a security evaluation on a simulated water treatment SCADA system using a Distributed Denial-of-Service (DDoS) attack. The work demonstrated how malicious attackers have the ability to disrupt the control and operation of a SCADA system using Modbus. The main aim of the work by Queiroz et al. was to propose a testbed architecture, and only a DDoS attack was discussed with no form of detection mechanism discussed.

To detect flooding attacks on the Modbus protocol, an IDS may be employed. An IDS is a software or hardware mechanism that detects misuse or unauthorised actions (Mell 2001). An example of a network IDS is Snort. Cheung et al. (Cheung et al. 2007) developed a model based detection approach for monitoring Modbus networks using Snort. More recently, Morris et al. (Morris et al. 2013) provided a set of 50 signature for Modbus and Modbus over serial links. These rules were developed to detect malicious activities on industrial control systems using the Modbus protocol specifications. However, no practical analysis or implementation of these rules were presented by Morris et al..

With Modbus as the de facto industrial communications protocol, and its widespread application in SCADA systems, an analysis and evaluation of Modbus flooding attacks is still considered an open problem. We focus on Modbus, and the use of anomaly-based, and signature-based detection techniques, to detect the onset of malicious activity aiming to disrupt normal operational control. We implement and analyse flooding specific rules and attacks on the Modbus protocol.

3 Modbus Flooding Attack

Modbus flooding attack is defined as one where the attacker is able to inject packets into the local network connecting the Human Machine Interface (HMI) and the control system and disrupting its normal operation. The attacker does not attempt to prevent messages from reaching the control system, it merely sends a larger than normal number of messages with selected function codes. The aim of the attacker is to control the system through this flood of messages and to effectively *drown* out legitimate commands from the HMI.

The Modbus protocol is particularly susceptible to this type of attack because the messages in the Modbus protocol do not include any authentication mechanisms that will allow the detection and rejection of injected false packets. Modbus messages also do not have any inherent checksum or integrity checking mechanisms, so it is much easier for the attacker

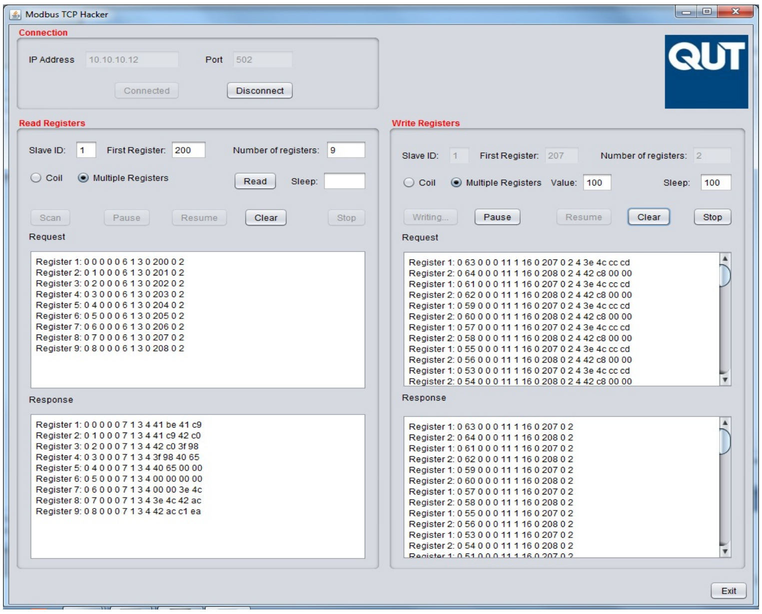


Figure 2: TCP Modbus Hacker Program

to flood the local network with false Modbus messages that the control system will accept.

For our experiments, we have developed software to conduct a flooding attack on a control system. This is described in the following section.

3.1 TCP Modbus Hacker

A simple Java application, *TCP Modbus Hacker*[1], was written to conduct a flooding attack on a Modbus control network. The Java application has two main functions; reading, and writing registers on the control system. These registers represent system actuators such as pumps and flow controls, as well as sensors such as water level sensors and temperature sensors. The software has the ability to query all the possible system registers to determine the active registers. This initial scan is important, as unfamiliar attackers will not know what registers are used by a particular control system. The software also allows an attacker to write to a single coil or multiple registers. As a result, the attacker can send commands to the control system that will be acted upon. The TCP Modbus Hacker has the ability to alter the speed of the commands sent to the target system by introducing a configurable sleep time in milliseconds between each command sent. The TCP Modbus Hacker also has the ability to pause and resume the attack at any time.

When the TCP Modbus Hacker is run against the target PLC, the PLC receives correct commands from the LabView HMI program at the same time. The TCP Modbus Hacker can generate process commands faster than the LabView HMI, and while the control system still tries to execute all the commands it receives, inevitably the control system only acts on the commands generated by the TCP Modbus Hacker. Figure 2 gives the graphical user interface for the TCP Modbus Hacker program.

[1] The authors acknowledge Vinh Tung Le and Pedram Mohammadian for implementing the TCP Modbus Hacker application

4 Modbus Flooding Attack Detection

This section presents the two attack detection techniques viz. anomaly-based detection (change detection algorithm) and signature-based detection (Snort), used for detecting the proposed Modbus flooding attacks.

4.1 Anomaly–based Detection

The onset of an anomalous activity such as flooding-based Denial-of-Service (DoS) attack, is generally accompanied by a change in the statistical properties of the parameters indicating the anomaly. Hence, the problem of detecting such anomalous activities can be transformed into a change detection problem with the aim to detect changes in the observed parameters with minimal delay and false detection rate (Tartakovsky et al. 2006*a*,*b*).

In order to detect such abrupt changes in the parameters being observed, various change detection techniques have been proposed and applied in different domains such as finance, network, image processing and seismology. Amongst all the different techniques that have been proposed, moving average, Cumulative Sum (CUSUM) and spectral analysis, are the most commonly used to detect anomalous network behaviour such as a flooding attack. The change detection technique used in this paper is a variant of the moving average technique called Exponentially Weighted Moving Average (EWMA). EWMA was chosen because of its simplicity, flexibility, robustness and effectiveness, especially in detecting high intensity attacks (Siris & Papagalou 2006) such as flooding-based attacks. It also has a lower false positive rate as compared to CUSUM for large dataset samples, or whenever the parameters are estimated (Khoo et al. 2011).

Change Detection Algorithm The change detection algorithm used in this paper, EWMA, examines the value of the observed parameter and determines if it has exceeded a particular threshold value. In comparison to other static threshold-based techniques, EWMA makes use of a dynamic (adaptive) threshold. This adaptive threshold is based on the

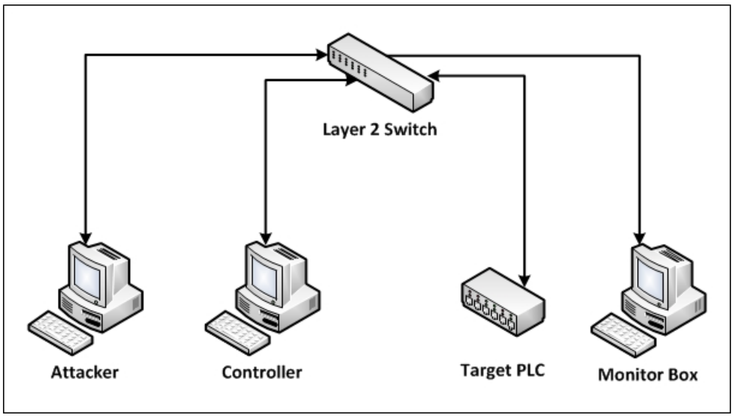


Figure 3: Experimental Set-up

estimated mean of the observed parameter, which in turn is computed from the recent observations. The computed threshold at every sampling interval is then used to make decisions about the changes detected in the parameter of interest, incoming TCP Modbus packets in this case.

Let x_t represent the number of TCP Modbus packets observed in the time interval t, and μ_{t-1} represents an average packet rate computed from measurements prior to t. Time t is a cardinal number and indicates a sampling time instance of the time series, rather than an actual time stamp. A significant change in x_t is indicated if,

$$x_t \geq (1+\eta)\mu_{t-1} \quad (1)$$

where $\eta > 0$ is a parameter indicating the fractional change from the mean (μ) that constitutes a 'change' or an indication of the anomalous behaviour of x_t i.e. number of incoming Modbus packets. It is to be noted that the change detection condition Equation 1 is used only to flag positive changes in the observed parameters.

The mean value μ_t of the parameter can be estimated, either using a sliding window, or via an EWMA of its previous occurrences until that time interval. The EWMA technique gives a maximum weight to the most recent observation, and an exponentially decreasing weight to older observations (Roberts 2000). In this paper, EWMA technique is used to calculate the mean value for the parameter of interest at each sampling time interval. Thus, the EWMA μ_t of the parameter x_t, as first studied by Roberts 2000, can be written as:

$$\mu_t = \lambda x_t + (1-\lambda)\mu_{t-1} \quad (2)$$

where

- x_t is number of packets observed at a time period t.
- μ_t is the EWMA value of x_t at a time period t.
- λ is the EWMA factor with a value between 0 and 1.

The value of x_t can either be an individually observed value, or an average computed using a given sampling period and technique. The value of λ determines the relative weight given to the most recent values of the mean parameter value computed before the current time interval.

Instead of flagging a change in the parameter being observed with every single occurrence of the threshold condition (Equation 1), the change detection technique has been slightly modified so that it triggers an alarm (an actual change) only after a minimum number of consecutive occurrences of threshold condition are detected. This is done to minimise the false alarms that would potentially arise due to erratic fluctuations in the number of packets being observed. Thus, an alarm is triggered when there are k consecutive time intervals for which the change detection condition occurs before flagging an actual change in the observed parameter.

$$\sum_{j=t-(k-1)}^{t} 1_{\{x_j \geq (1+\eta)\mu_{j-1}\}} \geq k \quad (3)$$

where $k \geq 1$ is a parameter indicating the number of consecutive time intervals for which the change detection condition is violated before flagging an actual change in the observed parameter.

The following section presents alternate signature-based attack detection technique using Snort.

4.2 Signature–based Detection

Snort (Roesch 1999) is an open source signature-based network IDS. Due to its wide deployment, Snort has become the de facto standard for intrusion detection. Snort captures network traffic utilising libpcap or winpcap libraries (depending on the platform it is deployed on) and decodes it. The purpose of the decode is to identify the type of network traffic. The decoded buffer is then made accessible to one or more Snort preprocessors. Preprocessors operate on the decoded buffer to perform appropriate transformations to the buffer. In the work presented in this paper, the Modbus preprocessor (Peterson 2009) is used. The transformed buffer is subsequently passed to the Snort detection engine, which detects traffic matching a signature or rule to generate alerts. Snort *alerts* may be generated by preprocessors or the detection engine, and specific detection rules can be specified to suit deployment.

Thus, similar to the change detection threshold discussed in Section 4.1, Snort rule thresholds can be applied as part of a Snort rule or as a stand-alone rule. Thresholds are applied to Snort rules to detect any changes in parameters which result from anomalous traffic such as a flooding-based DoS traffic.

The typical format of the Snort threshold[2] rule is as follows `threshold: type threshold, track <by_src|by_dst>, count <c>, seconds <s>;`. The

[2]The `threshold` rule has been deprecated and will not be available in future. However additional event processing filter (`event_filter`) is available to implement threshold checking.

threshold rate may be tracked by the traffic source address (*by_src*) or destination (*by_dst*) address, for a count (c), which specifies the number of alerts within the time specified as time in seconds (s).

To prevent the *false-positive* paradox, the threshold values employed in the Snort rule need to be based on some statistical mean of normal traffic. Alternatively, the threshold values may be derived experimentally, to ensure that no false positive alerts are generated as a result of the threshold rules.

Since the attacks described in Section 3.1, floods TCP port 502 to write to a single coil (Modbus function code `0x05`), the Snort rules may be refined further to alert on specific Modbus traffic. As Snort provides a Modbus preprocessor, specific rules can be written to examine the contents of the Modbus payload. Modbus TCP packets contain a MBAP Header and PDU as illustrated in Figure 1, and patterns in these may be matched using the content keyword.

The typical content option is in the format `(content:[!]‘‘<content string>’’;)`. Additionally modifiers such as `offset`, `depth` and `byte_test` are used to specify the offset into the payload, how far from the offset to search, and how many bytes to convert to find the function code. Content specific rules can be applied together with threshold rules to get higher accuracy detection of the attacks

5 Experimental Set-up and Methodology

This section describes the experimental set-up and methodology used for generating the attack and benign traffic used in this paper.

5.1 Experimental Set-up

A typical SCADA architecture comprises a human operator, a HMI, a Master Telemetry Unit (MTU), a data communications network and Remote Telemetry Units (RTUs). The human operator monitors the SCADA system and performs supervisory control function via the HMI, which presents data and allows for control inputs. The MTU transmits the control information and collates the data for presentation to the HMI. The RTU receives control information via the data communications network from the MTU and manipulates the field devices under its control. The RTU is also responsible for acquiring data from field devices and transmitting them to the MTU. The communication between the MTU and RTU is implemented using a SCADA protocol.

In the case of the experimental set-up, as illustrated in Figure 3, the LabView application on the Controller provides both the HMI and MTU functionality. A conventional Ethernet network is utilised as the data communications network. The Target PLC using a National Instruments Compact RIO provides RTU functionality, and Modbus is utilised as the SCADA protocol.

The experimental set-up used for generating the required normal and attack traffic, consists of three machines, a PLC and a layer 2 network switch connecting all the devices. Figure 3 gives an overview of the experimental set-up. The three machines used in the testbed are standard PCs with 3.0 GHz Intel Core2 processors, 4 GB of memory, and a main 1 Gb Network Interface Card (NIC). Of these three machines, one is used as an *Attacker* and runs an instance of the TCP Modbus Hacker program previous described (see Section 3.1 for details). The two remainder machines are used to act like a *Controller* (running LabView HMI) and *Monitor Box* (running `tcpdump`) respectively. The *Target PLC* is a National Instruments Compact RIO 9074, with a Universal Analog Input Card (NI9219), a 20mA Analog Input Card (NI9203), a 10V Analog Output Card (NI9263), and a High Speed 24V Digital Output Card (NI9474).

This PLC controls the process setup show in Figure 5. The process setup is of two tanks, a lower reservoir tank and an upper holding tank. A pump cycles water into the upper tank, which then drains back into the lower tank. Various instrumentation measure the temperature, pressure and level of each tank, with flow indicators measuring the flow of water in both pipelines. The flow control valve controls the flowback of water into the lower reservoir. For this paper, we launch a packet flooding attack on the pump in an attempt to control the pump. The HMI, for this process setup is shown in Figure 4. Built in LabView, it shows the controllers view of the process.

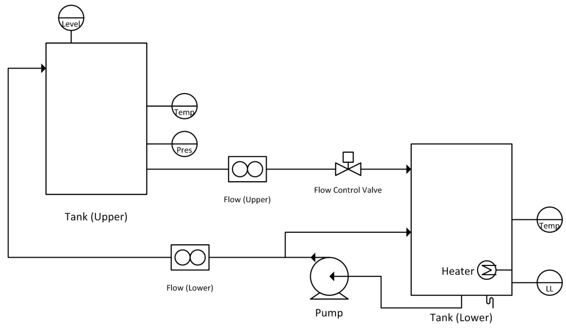


Figure 5: Process and Instrumentation Diagram

5.2 Methodology

The experiment was conducted with two parties, the Controller and Attacker over a period of 180 seconds, using the set-up shown in Figure 3. The Controller attempted to control the pump, shown in Figure 5, with it being on (state 1) for the first 30 seconds, and being turned off (state 0) for the next 30 seconds, combining into a 60 second periodic cycle that was repeated three times as shown in Figure 6a. The Attacker attempted to disrupt control of the pump by launching a flooding attack using the TCP Modbus Hacker program previously discussed (Section 3.1).

As shown in Figure 6b, the Attacker lays dormant in the time period of 0-60 seconds. In the time period of 61-90 seconds, the Attacker floods the PLC with state 0 packets, opposite to the Controller state in the same time period. When the Controller state switches to state 0 at 91 seconds, the Attacker state changes to 1 and begins to flood the PLC with state 1 packets. At 120 seconds, the Attacker returns to dormant state, and ceases the attack. This experiment was repeated for different values of *Sleep* time, a parameter within the TCP Modbus Hacker program, which allows to set the inter-packet delay, in millisecond (ms), between outgoing packets. For this paper, three sets of experiments were conducted using 0ms, 50ms and 100ms as the sleep time value. These values were chosen to simulate the Attacker's attempt to avoid detection, whilst still successfully flooding the Target PLC. All the generated traffic for the three variants of the flooding attack were captured on the Monitor Box. The captured traffic was then analysed in an *off-line* manner using two detection techniques viz. change detection algorithm and signature-based attack detection via Snort. The following section presents the obtained results and analysis.

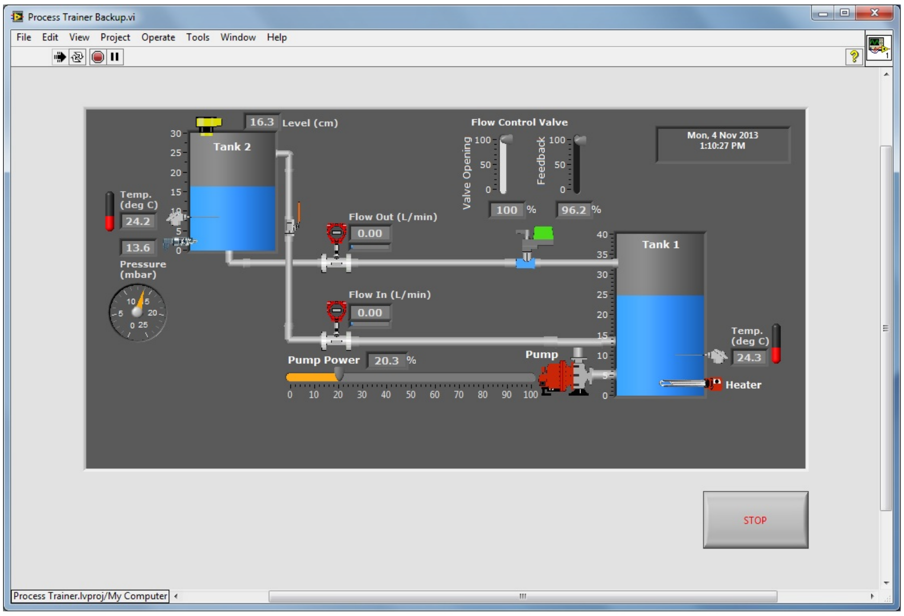
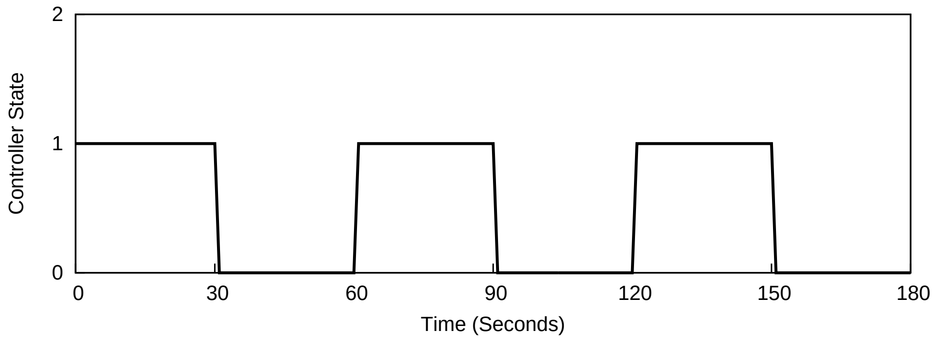
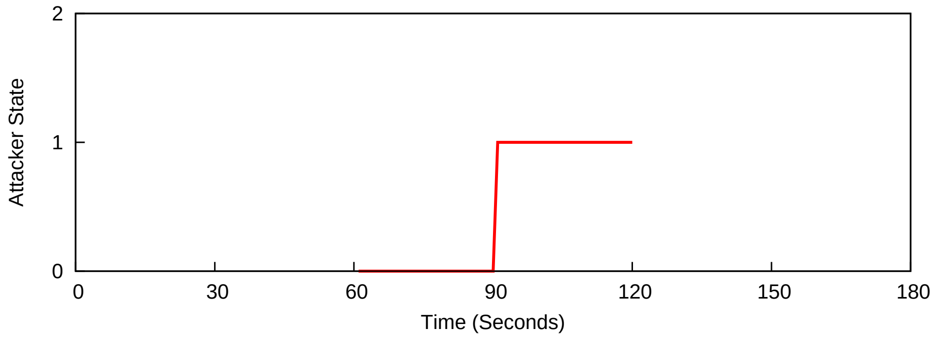


Figure 4: LabView HMI



(a) Controller States over Time.

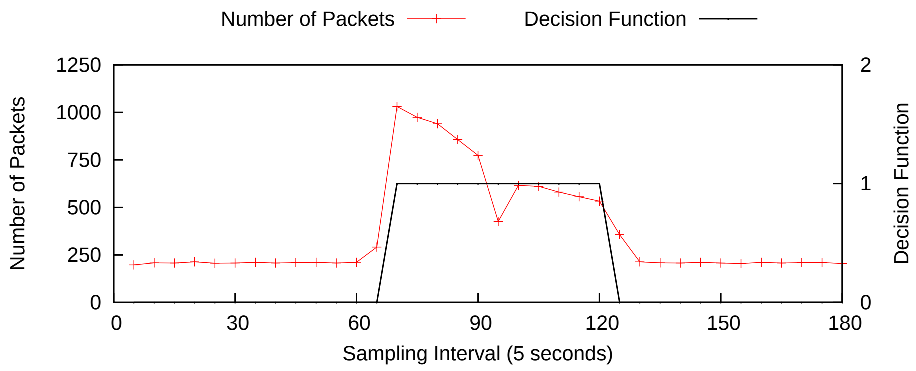


(b) Attacker States over Time.

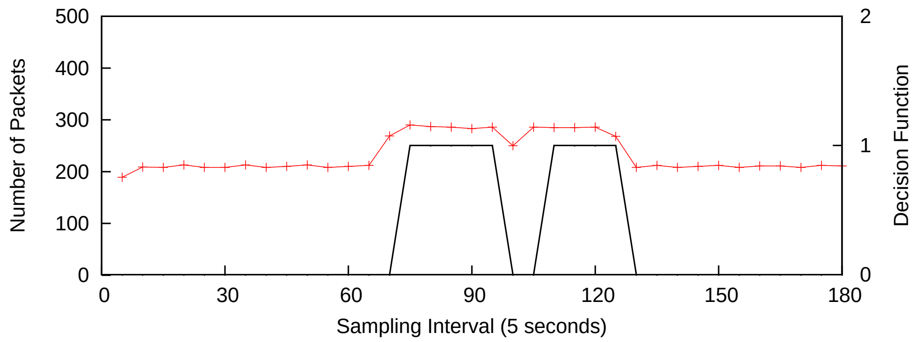
Figure 6: Traffic Generation Scenario

6 Experimental Results and Analysis

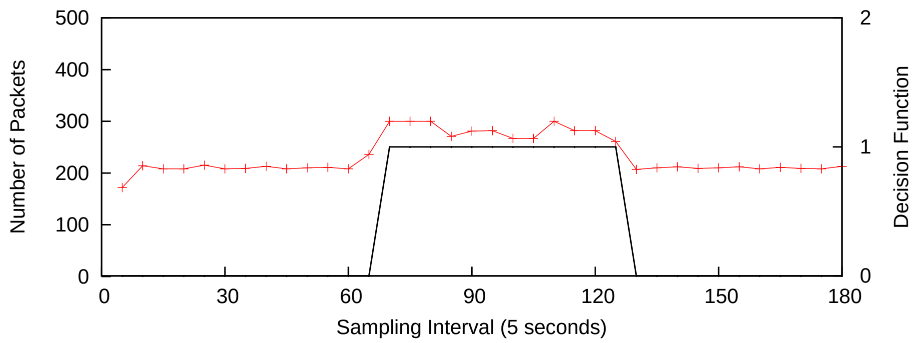
The flooding attack launched on the Target PLC as described in Section 5.2 was successful in overwhelming the PLC for the three variations in sleep time. In the attack time period of 61 to 90 seconds of the experiment, the pump was successfully turned off as the Attacker was flooding the Target PLC with state 0 commands. The HMI on the Controller was still showing the pump as running (state 1). In the time period of 91 to 120 seconds, the Controller turned the pump off by changing the pump state to 0. However, the Attacker reversed the flooding attack state to 1, and was successful in turning on the pump, whilst the Controller HMI depicted the pump as turned off. The 0ms sleep time was the most responsive in changing the running status of the pump and occurred within 1 to 2 seconds of launching the attack. The attacks using a sleep time of 50ms and 100ms were also successful in changing the running status of the pump.



(a) Modbus flooding attack with 0ms sleep.



(b) Modbus flooding attack with 50ms sleep.



(c) Modbus flooding attack with 100ms sleep.

Figure 7: Modbus flooding attack detection using change detection algorithm

However, the Target PLC was relatively slower to respond to these attacks.

This section presents the experimental results obtained by running the anomaly-based change detection algorithm and a signature-based detection (Snort) against the attacks. It also presents a comparative analysis on the two attack detection techniques.

6.1 Anomaly–based Detection

In this section, the change detection algorithm described previously in Section 4.1 is used to detect the flooding attacks. Different values for the four configurable parameters – η, λ, k, T – were initially based on the previous work done in change detection using EWMA (Montgomery 2007, Paul 2006, Khoo et al. 2011, Siris & Papagalou 2006). These values were then experimentally optimised to improve the detection accuracy. Once optimised, the values were kept constant for all three attack datasets. Unless stated otherwise, the values considered for these parameters are $\eta = 0.25$, $\lambda = 0.98$, $k = 2$, $T = 5$.

The experimental results obtained by running the EWMA-based change detection algorithm on the number of incoming packets to the target PLC are shown in Figure 7. The graph plots number of packets on the left y-axis against time (sampled every 5 seconds). The output of the decision function is shown on the right y-axis, with 0 indicating no-change (normal traffic) and 1 representing the change (attack) detected in the number of incoming packets to the PLC over a period of 180 seconds.

The change detection is able to successfully detect all the three attacks with the decision function indicating 1 for the attack period, as shown in Figures 7a, 7b and 7c. A small lag between the start of the attack

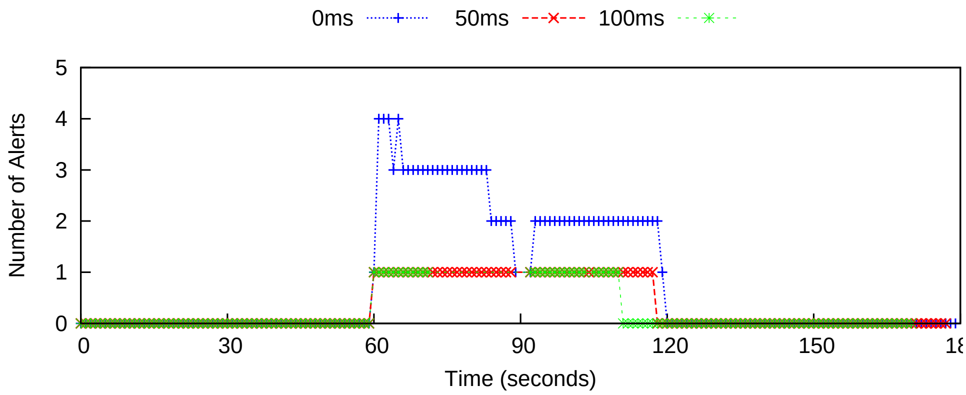


Figure 8: Modbus flooding attack detection using Snort

at the 61^{st} second and the output of the decision function is due to the selected value of k, 2 in this case, which flags a change only after 2 consecutive violations of the change detection condition (Equation 3). Setting a lower value of k such as 1 would remove this lag, however, would also result in flagging small fluctuations in the observed traffic, thereby increasing the number of false alarms.

A small dip is observed around the 95^{th} second, especially in Figures 7a and 7b. This is mainly due to a switch in the attackers activity i.e. from trying to turn-off the pump (flooding with packets with 0s) to turn it on (flooding with packets with 1s), opposite to the controllers activity. This switching of activity from the attacker is accompanied by a delay in response from the Target PLC and hence a drop in the number of incoming packets. This drop in the number of incoming packets affects the adaptive threshold value in the attack with 50ms delay, Figure 7b, which thereby causes the decision function momentarily drop around the 100^{th} second mark, before going back to 1 and detecting the remainder of the attack.

6.2 Signature–based Detection

An alternative to the anomaly-based detection using the change detection algorithm, a signature-based detection technique using Snort was also used. This was primarily done to test if Snort, being the industrial de-facto for intrusion detection, can be used to detect the proposed flooding attack. The preliminary results obtained using Snort with customised rules are discussed below.

To enable Snort to detect the proposed Modbus flooding attacks, the following rule was utilised:

```
alert tcp any any -> 10.10.10.12 502
(msg:"Modbus threshold violation";
sid:1000001; rev:1; priority:1;
threshold:type threshold, track by_dst,
count 50, seconds 1;).
```

This rule utilised the Modbus preprocessor for Snort together with the threshold directive as described in Section 4.2. The initial normal (non-attack) network traffic, i.e. traffic between 0 s and 60 s (see Figure 6) from the Controller to the TCP port 502 on the Target PLC was observed to be, on average, 42 packets per second. This value was adjusted experimentally to obtain the value of 50 packets per second. Employing this value ensured that there were no false alerts generated in the initial non-attack period. Thus, the Snort rule threshold value employed a count of 50 packets for 1 second period. These values are specific to the scenario, and will need to be changed to suit the specific environment that Snort is deployed in.

Figure 8 plots the number of alerts generated against time in seconds. Using Snort with the aforementioned rule, the Snort IDS was able to successfully detect the onset of anomalous activities in all the three variants of the flooding attack. In the case of attack with 0ms sleep, the number of alerts triggered were higher as compared to the attacks with 50ms and 100ms delay. This is speculated to be an artifact of Snort, which uses a sliding-window-based time period to perform the rate calculations and is used to determine if there is an rule violation and subsequently trigger an alert. Thus, with the 0ms attack, as there are a large number of packets violating the threshold in comparison to the 50ms and 100ms attacks, there are more of these sliding-windows triggering alerts.

It should also be noted that the number of alerts, while interesting (and indicating a greater likelihood of a flooding attack) should not detract from the fact that any alerts should be investigated. A detailed analysis of the use of a signature-based technique needs further investigation and constitutes the future work of this research.

6.3 Comparative Analysis

The two techniques used in this paper, anomaly-based change detection algorithm and signature-based detection via Snort, successfully demonstrate that abnormal activities started at the 60^{th} second and finished at the 120^{th} second. The two techniques, while completely orthogonal, do possess their respective advantages and disadvantages. Whereas the signature-based detection requires a predefined threshold which is fixed, the change detection algorithm does not require any pre-defined threshold. Instead, the threshold is adaptively calculated and changes continuously with the observation time. In terms of implementing the attack detection technique in a real-world scenario, signature-based detection is easier to deploy than the anomaly-based change detection algorithm, as Snort already provides a preprocessor for Modbus, and thus can be used to detect attacks using this protocol. However, in either of the two detection techniques, values of the configurable parameters/threshold used are scenario dependent and thus require optimisation.

7 Conclusion and Future Work

The work described in this paper has explored the area of cyber attacks in industrial control systems. In particular we have investigated flooding attacks on the commonly used Modbus control systems protocol. The work in this paper has shown that flooding attacks can disrupt the functionality of physical systems. The paper also investigated anomaly-based and signature-based techniques for detecting these attacks. Both of the intrusion detection techniques are shown to be successful in detecting the flooding attack. However, signature-based systems are dependent on threshold values, while the anomaly-based change detection algorithm takes time to react to the attack. Future work includes investigating how vulnerable the Modbus protocol is to other types of attacks such as man in the middle attacks, and to investigate and compare different intrusion detection techniques for these new attacks. Mitigation strategies such as integrating checksums and authentication mechanisms need to be developed to improve the security of the Modbus protocol to make industrial control systems more secure.

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