

## Chapter 5

# A TAXONOMY OF ATTACKS ON THE DNP3 PROTOCOL

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**Abstract** Distributed Network Protocol (DNP3) is the predominant SCADA protocol in the energy sector – more than 75% of North American electric utilities currently use DNP3 for industrial control applications. This paper presents a taxonomy of attacks on the protocol. The attacks are classified based on targets (control center, outstation devices and network/communication paths) and threat categories (interception, interruption, modification and fabrication). To facilitate risk analysis and mitigation strategies, the attacks are associated with the specific DNP3 protocol layers they exploit. Also, the operational impact of the attacks is categorized in terms of three key SCADA objectives: process confidentiality, process awareness and process control. The attack taxonomy clarifies the nature and scope of the threats to DNP3 systems, and can provide insights into the relative costs and benefits of implementing mitigation strategies.

**Keywords:** Distributed Network Protocol (DNP3), attacks, attack taxonomy

## 1. Introduction

In September 2007, CNN released dramatic footage of the “Aurora” test involving a cyber attack on an electric generator. The test conducted by Idaho National Laboratory (INL) scientists caused the generator to “shudder, shake, then go up in smoke – destroyed just as effectively as if with a smuggled bomb” [8].

The INL test underscores the vulnerability of the electrical power grid to cyber attack. Of particular concern are supervisory control and data acquisition (SCADA) systems that monitor and control vital equipment throughout the power grid [5, 7]. Attacks on SCADA systems, possibly launched over the Internet, can disrupt electrical power generation and transmission, and even cause physical destruction of key assets as in the Aurora experiment.

This paper focuses on attacks on the Distributed Network Protocol (DNP3), which defines how SCADA devices communicate control commands and data. DNP3 is the primary SCADA protocol used in the electrical power grid. According to EPRI [4], more than 75% of North American electric utilities currently employ DNP3. Meanwhile, DNP3 is also being used in other critical infrastructure sectors, including oil and gas distribution, and water supply [3].

DNP3 attacks fall into three categories: attacks that exploit the DNP3 specifications, attacks that exploit vendor implementations, and attacks that target the underlying infrastructure. We focus on attacks in the first category, which target all SCADA systems that conform with the DNP3 standard.

Our analysis of the DNP3 protocol has identified 28 attacks. The attacks assume the ability to sniff DNP3 traffic and/or craft and inject messages. Each instance or manifestation of an attack is inserted in a taxonomy based on threat category and target. The threat categories considered are interception, interruption, modification and fabrication. The targets are the control center (master unit), outstation devices and network/communication paths. Each attack is associated with the specific DNP3 protocol layer it exploits. Thus, a separate taxonomy is presented for each of the three principal DNP3 protocol layers: data link layer, pseudo-transport layer and application layer.

Because of space constraints, it is not possible to describe all 28 attacks. However, fifteen representative attacks, with effects ranging from obtaining device configuration data to disabling or spoofing the master unit, are discussed. Also, the impact of the attacks is evaluated with respect to the principal SCADA objectives of process confidentiality, process awareness and process control. The attack taxonomy clarifies the nature and scope of the threats to DNP3 systems and, consequently, supports the application of formal risk analysis and threat mitigation strategies.

## 2. DNP3 Protocol

DNP3 was developed by Westronic, Inc. (now GE Harris) in the early 1990s. The protocol defines how devices in a SCADA system communicate control commands and process data [15].

DNP3 supports three simple communication modes between a control center (master unit) and outstation devices [1]. In a unicast transaction, the master sends a request message to an addressed outstation device, which responds with a reply message. For example, the master may send a “read” message (e.g., request an amperage reading) or a “write” message to perform a control action (e.g., trip a circuit breaker); the outstation responds with the corresponding message (e.g., the amperage reading, an acknowledgement that the circuit breaker was tripped, or an error message). In a broadcast transaction, the master sends a message to all the outstations in the network (e.g., a “write” message that resets amperage sensors); the outstation devices do not reply to the broadcast message. The third communication mode involves unsolicited responses from outstation devices; these responses are typically used to provide periodic updates or alerts (e.g., an amperage reading exceeds a threshold).

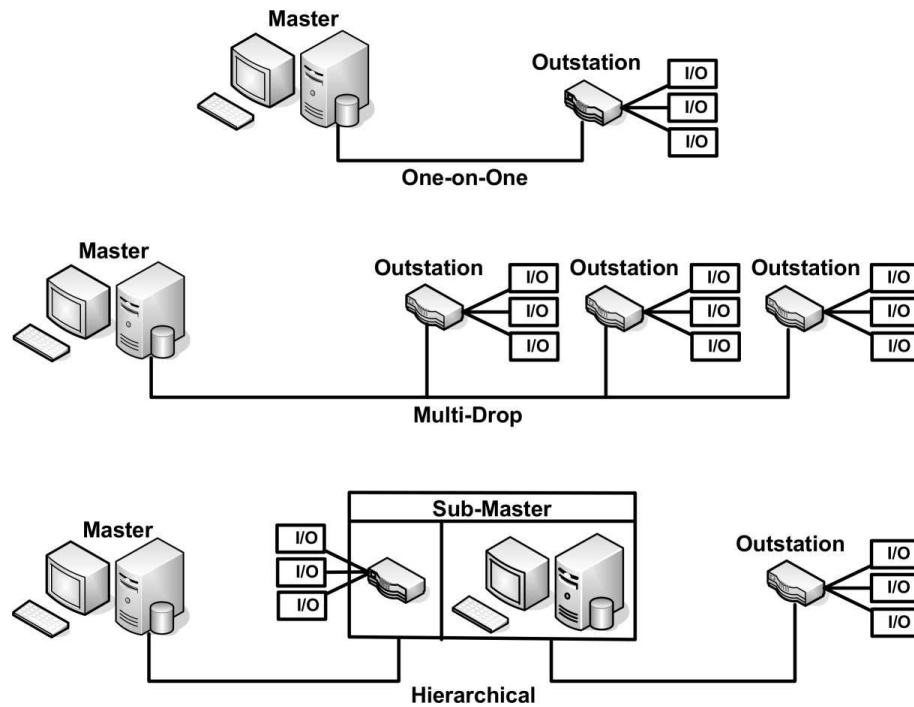


Figure 1. DNP3 network configurations.

The DNP3 protocol supports a variety of network configurations. Three common configurations are shown in Figure 1 [2]. In a “one-on-one” configuration, one master and one outstation device share a dedicated connection such as a dial-up telephone line. The popular “multi-drop” configuration has one master that communicates with multiple outstations. Every outstation receives every request from the master, but each outstation only responds to messages addressed to it. In a “hierarchical” configuration, a device acts as an outstation in one segment and a master in another segment; such a dual-purpose device is called a “sub-master.”

Early SCADA architectures often relied on communication circuits that were susceptible to noise and signal distortion. Consequently, DNP3 was designed to incorporate multiple protocol layers. The International Electrotechnical Commission (IEC) initially proposed the IEC 870 standard for telemetry data transmission in SCADA systems based on the Open Systems Interconnection (OSI) model [1]. This three-layer Enhanced Performance Architecture (EPA) was created by eliminating superfluous layers (from the point of view of SCADA systems) from the seven-layer OSI model (Figure 2). However, EPA did not support application layer messages that were larger than the maximum length of a data link frame. DNP3 addressed this issue by incorporating a pseudo-transport layer to allow message fragmentation (Figure 2).

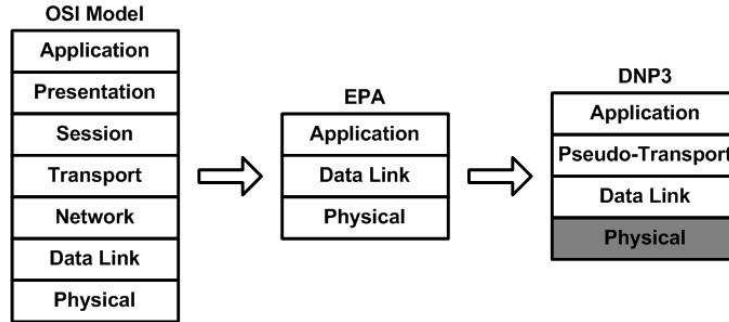


Figure 2. Design progression from OSI to DNP3.

The DNP3 protocol layers are placed on top of a physical layer, which is responsible for transmitting messages over physical media such as radio, satellite, copper and fiber [15]. The physical layer specification determines the electrical settings, voltage and timing, along with other properties necessary to send signals between devices. The physical layer provides five services: (i) send data, (ii) receive data, (iii) connect, (iv) disconnect, and (v) status update. Note that the physical layer is shaded in Figure 2 because it is not specified in the DNP3 standard.

DNP3 may be transported over a variety of physical media, including old-fashioned serial links. However, modern SCADA systems typically use DNP3 in IP networks. The DNP Users Group has stipulated that the three layers of DNP3 not be modified in IP-based implementations [14]. For this reason, the three DNP3 layers are placed directly above the TCP/IP or UDP/IP layers in the protocol stack.

The attack taxonomy described in this paper is intended to apply to all DNP3 implementations, serial as well as TCP/IP. Consequently, we only consider attacks that exploit the three DNP3 layers common to all implementations – the data link, pseudo-transport and application layers.

## 2.1 Data Link Layer

The data link layer maintains a reliable logical link between devices to facilitate the transfer of message frames [12]. A data link layer frame has a 10-byte fixed size header and a data or “payload” section containing data passed down from the pseudo-transport and application layers. The maximum length of the data section is 250 bytes (282 bytes including 16-bit CRC fields for every 16 bytes of data). Thus, the maximum length of a data link frame is 292 bytes.

Figure 3 shows the format of a data link header. The Start field always contains the two-byte value 0x0564 to enable the receiver to determine where the frame begins; the Start bytes signal that a DNP3 packet has arrived and must be processed. The Length field provides the number of bytes in the remainder of the frame (not including CRCs).

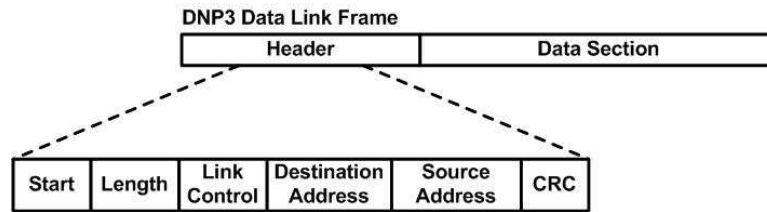


Figure 3. DNP3 data link frame.

The Link Control field in the data link header contains data that controls message flow, provides sequencing and determines the function of the frame. This data helps determine if the device is a master or outstation, identifies the device that initiated the communication, and provides the status of the logical link. The Link Control field also contains a four-bit function code that specifies the purpose of the message. Separate sets of function codes are used in messages originating from a master and in those originating from outstation devices. Examples of master function codes are reset remote link, reset user process, request link status and test function. Outstation device function codes include positive acknowledgement, message not accepted, status of link and no link service. The Link Control field also contains two flags for communication synchronization and flow control. The 16-bit Destination Address in the data link header specifies the intended recipient (which may include a broadcast address of 0xFFFF); the 16-bit Source Address identifies the originator. A 16-bit CRC is also included in the header to verify the integrity of the transmission.

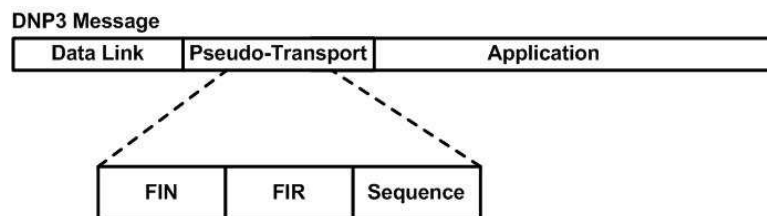


Figure 4. DNP3 pseudo-transport message fields.

## 2.2 Pseudo-Transport Layer

The DNP3 pseudo-transport layer handles message fragmentation and re-assembly [10]. As mentioned above, it enables application messages larger than one data link frame in length to use multiple frames. The pseudo-transport layer adds one byte containing the FIR and FIN flags and a Sequence number (Figure 4). The FIR and FIN flags indicate the first and final frames of a fragmented message, respectively. The Sequence number, which is incremented for each successive frame, is used to reassemble messages for processing by the

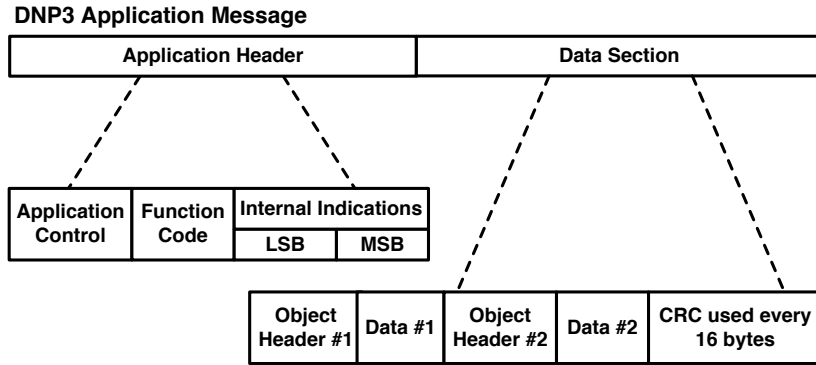


Figure 5. DNP3 application message.

application layer. The sequencing information also facilitates the detection of dropped frames.

### 2.3 Application Layer

The application layer, which specifies DNP3 request and reply messages [11], defines the roles of the master and outstation devices. A request message from a master directs an outstation device to perform a task, collect and provide data, or synchronize its internal clock. Only a master may send request messages; outstation devices may send solicited or unsolicited messages. The application layer fragments messages that exceed the maximum fragment size (determined by the size of the receiver's buffer). A typical message fragment is between 2048 and 4096 bytes.

Figure 5 shows the format of the application layer header. The Application Control field performs a similar function as the corresponding field in the pseudo-transport layer, but at a higher level. Two flags are included to specify the first or last fragment of a message and the sequence number for ordering and reassembly. An additional flag is included to request confirmation upon receipt of a fragment.

The Function Code field communicates the purpose of a message. This field is used in both requests and replies, but the available functions change with the message type. The 23 defined function codes for request messages are grouped into six categories: (i) transfer functions, (ii) control functions, (iii) freeze functions, (iv) application control functions, (v) configuration functions, and (vi) time synchronization functions.

A reply message can be a: (i) confirmation, (ii) response, or (iii) unsolicited response. Reply message headers incorporate a two-byte Internal Indications (IIN) field that communicates useful information about the outstation unit to the master. Each bit in the IIN field has a specific meaning that is updated in every reply message. Example IIN codes are time synchronization required, de-

vice restart, invalid parameters, function code not implemented and requested objects unknown.

Following the header in a DNP3 application layer message are data objects that convey encoded representations of data (Figure 5). Several data objects are defined to enable devices running on different platforms to efficiently communicate data and commands. Examples of data objects are binary inputs, binary outputs, analog inputs, analog outputs and counters.

### 3. Attack Taxonomy Development

Attacks on DNP3 systems fall into three categories: (i) attacks that exploit the DNP3 specifications, (ii) attacks that exploit vendor implementations of DNP3, and (iii) attacks that exploit weaknesses in the underlying infrastructure. Attacks on vendor implementations typically exploit configuration errors or code flaws (e.g., via buffer overflows). Attacks on the underlying infrastructure exploit vulnerabilities in information technology, network and telecommunications assets, or weak security policies. We focus on attacks that exploit the protocol specifications, which target all SCADA systems that conform with the DNP3 standard.

Attack identification involves a detailed analysis of the DNP3 protocol. DNP3 was not designed with security in mind. Consequently, security is a major concern for DNP3 implementations that use commodity computing equipment and networking technologies [3]. Protocol analysis helps identify weaknesses and enhance security awareness, enabling vendors and asset owners to design architectures, configure equipment and operate systems in a manner that addresses the identified vulnerabilities.

Our methodology, which was recently used to develop attack taxonomies for the Modbus Serial and TCP protocols [6], involved analyzing the DNP3 protocol specification and identifying weaknesses. Attacks were then formulated to exploit these weaknesses. Each attack was analyzed for its ability to intercept, interrupt, modify and/or fabricate [9] each of the three primary targets: master, outstation devices and network/communication paths. Figure 6 [13] illustrates the four threat categories considered in the DNP3 attack taxonomy.

The identified attacks are classified based on the threat categories and DNP3 targets. Each attack has various manifestations or “instances.” For example, the Outstation Data Reset attack reinitializes data objects in an outstation device to values inconsistent with the state of the system, which can affect the operation of the targeted device. Thus, there are two instances of this application layer attack: modifying an outstation and interrupting an outstation.

The attack instances are organized within attack taxonomies for the three layers common to all DNP3 implementations – the data link, pseudo-transport and application layers (Tables 1–3). Classifying attacks within a taxonomy supports formal risk analysis strategies. In particular, a taxonomy can be used to systematically examine mitigation strategies, evaluate attack impact and clarify the magnitude of the threats. Moreover, a taxonomy helps raise awareness about vulnerabilities.

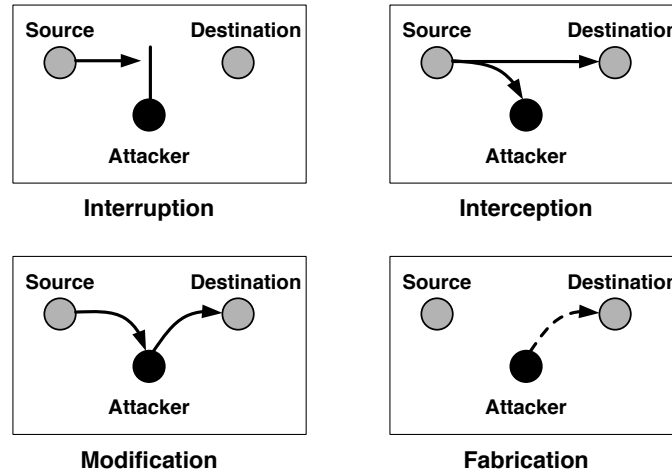


Figure 6. Threat categories [13].

The theorized attacks assume the ability to sniff DNP3 traffic, and/or to craft and inject messages. Note that message modification and fabrication require the appropriate CRC values to be computed and inserted in messages. Principal entry points for attacks include the master, outstation devices and network components. The entry points are, of course, dependent on an attacker's access and intent. The attacks are effective on all SCADA systems that conform with the DNP3 specifications. Of course, if certain aspects (e.g., DNP3 function codes) are not implemented by a vendor, the corresponding attacks (that exploit the unimplemented function codes) would not work.

#### 4. DNP3 Attack Taxonomy

DNP3 attacks are organized according to the specific protocol layers they exploit. Tables 1, 2 and 3 present the attack taxonomies for the data link layer, pseudo-transport layer and application layer, respectively. The rows of the tables identify the threat categories while the columns list the targeted assets. Attacks that are common (C) to all three layers are designated by Cx; Cx-y denotes the  $y^{th}$  instance of the Cx attack. Likewise, attack instances associated only with the data link layer, pseudo-transport layer and application layer are denoted by Dx-y, Px-y and Ax-y, respectively. For example, the Rogue Interloper attack, which is common to all three DNP3 layers, is designated as C3, and its twelve instances are denoted by C3-1 through C3-12.

Because of space constraints it is not possible to describe all 28 attacks. However, several representative attacks are discussed. First, representative attacks common to all three DNP3 layers are presented. Next, representative attacks specific to the data link, pseudo-transport and application layers are described. These attacks and the corresponding taxonomies shed light on the nature and scope of the security threats facing DNP3 systems.



## 4.1 Common Attacks

As mentioned above, most of the attacks rely on the ability to intercept, modify and/or fabricate DNP3 messages. DNP3 implementations typically do not employ encryption, authentication and authorization; DNP3 devices simply assume that all messages are valid. Three attacks leverage these weaknesses and, because of their flexibility, target all three DNP3 layers. The three common attacks (with 21 attack instances) described below are among the most insidious because they perform reconnaissance and/or execute potentially malicious operations on outstation devices while (possibly) masking their actions.

- **Passive Network Reconnaissance (C1):** An attacker with the appropriate access captures and analyzes DNP3 messages. This attack provides the attacker with information about network topology, device functionality, memory addresses and other data. Tables 1–3 list three instances of this attack: interception of master data (C1-1); interception of outstation device data (C1-2); and interception of network topology information (C1-3).
- **Baseline Response Replay (C2):** An attacker with knowledge of normal DNP3 traffic patterns simulates responses to the master while sending fabricated messages to outstation devices. Tables 1–3 list six instances of this attack: interruption of the master (C2-1) and outstation (C2-2); modification of the master (C2-3) and outstation (C2-4); and fabrication of the master (C2-5) and outstation (C2-6).
- **Rogue Interloper (C3):** An attacker installs a “man-in-the-middle” device between the master and outstations that can read, modify and fabricate DNP3 messages and/or network traffic. Tables 1–3 list twelve instances of this most serious attack: interception of master (C3-1), outstation (C3-2) and network data (C3-3); interruption of the master (C3-4), outstation (C3-5) and network (C3-6); modification of the master (C3-7), outstation (C3-8) and network path (C3-9); and fabrication of the master (C3-10), outstation (C3-11) and network path (C3-12).

## 4.2 Data Link Layer Attacks

Twelve attacks (including the three common attacks described above) and 54 attack instances (including 21 instances for the three common attacks) were identified for the data link layer (Table 1). Most of the attacks involve intercepting DNP3 messages, modifying message values and sending them to the master or outstation devices. Some of the attacks impact confidentiality by obtaining configuration data and network topology information. Integrity attacks insert erroneous data or reconfigure outstations. Attacks on availability cause outstation devices to lose key functionality or disrupt communications with the master. We discuss five data link layer attacks in more detail.

Table 1. Attack taxonomy for the DNP3 data link layer.

12 Attacks 54 Instances	Master	Outstation	Network
<b>Interception</b>	C1-1 C3-1	C1-2 C3-2	C1-3 C3-3
<b>Interruption</b>	C2-1 C3-4 D1-1 D2-1 D3-1 D7-1 D8-1 D9-1	C2-2 C3-5 D1-2 D2-2 D3-2 D4-1 D5-1 D8-2 D9-2	C3-6 D3-3 D6-1 D8-3 D9-3
<b>Modification</b>	C2-3 C3-7 D2-3 D6-2 D8-4 D9-4	C2-4 C3-8 D2-4 D5-2 D8-5 D9-5	C3-9 D8-6 D9-6
<b>Fabrication</b>	C2-5 C3-10 D8-7 D9-7	C2-6 C3-11 D8-8 D9-8	C3-12 D8-9 D9-9

- **Length Overflow Attack (D2):** This attack inserts an incorrect value in the Length field that affects message processing. The attack can result in data corruption, unexpected actions and device crashes. Table 1 lists four instances of the attack: interruption of the master (D2-1) and outstation (D2-1); and modification of the master (D2-3) and outstation (D2-4).
- **DFC Flag Attack (D4):** The DFC flag is used to indicate that an outstation is busy and that a request should be resent at a later time. This attack sets the DFC flag, which causes an outstation device to appear busy to the master. Table 1 lists the one instance of this attack: interruption of an outstation (D4-1).
- **Reset Function Attack (D5):** This attack sends a DNP3 message with Function Code 1 (reset user process) to the targeted outstation. The attack causes the targeted device to restart, rendering it unavailable for a period of time and possibly restoring it to an inconsistent state. Table 1 lists two instances of this attack: interruption of an outstation (D5-1); and modification of an outstation (D5-2).
- **Unavailable Function Attack (D7):** This attack sends a DNP3 message with Function Code 14 or 15, which indicates that a service is not functioning or is not implemented in an outstation device. The attack causes the master not to send requests to the targeted outstation because it assumes that the service is unavailable. Table 1 lists the one instance of this attack: interruption of the master (D7-1).
- **Destination Address Alteration (D8):** By changing the destination address field, an attacker can reroute requests or replies to other devices causing unexpected results. An attacker can also use the broadcast address 0xFFFF to send erroneous requests to all the outstation devices; this attack is difficult to detect because (by default) no result messages are

returned to a broadcast request. Table 1 lists nine instances of this attack: interruption of the master (D8-1), outstation (D8-2) and network (D8-3); modification of the master (D8-4), outstation (D8-5) and network path (D8-6); and fabrication of the master (D8-7), outstation (D8-8) and network path (D8-9).

Table 2. Attack taxonomy for the DNP3 pseudo-transport layer.

5 Attacks 31 Instances	Master	Outstation	Network
<b>Interception</b>	C1-1 C3-1	C1-2 C3-2	C1-3 C3-3
<b>Interruption</b>	C2-1 C3-4 P1-1 P2-1	C2-2 C3-5 P1-2 P2-2	C3-6
<b>Modification</b>	C2-3 C3-7 P2-3	C2-4 C3-8 P2-4	C3-9 P2-5
<b>Fabrication</b>	C2-5 C3-10 P2-6	C2-6 C3-11 P2-7	C3-12 P2-8

### 4.3 Pseudo-Transport Layer Attacks

The pseudo-transport layer provides less functionality than the other layers; thus, fewer attacks are associated with this layer. The taxonomy in Table 2 lists five attacks (including the three common attacks) and 31 attack instances (including 21 instances for the common attacks). The two attacks associated with the pseudo-transport layer target the fragment flags and sequence number.

- Fragmented Message Interruption (P1):** The FIR and FIN flags indicate the first and final frames of a fragmented message, respectively. When a message with the FIR flag arrives, all previously-received incomplete fragments are discarded. Inserting a message with the FIR flag set after the beginning of a transmission of a fragmented message causes the reassembly of a valid message to be disrupted. Inserting a message with the FIN flag set terminates message reassembly early, resulting in an error during the processing of the partially-completed message. Table 2 lists two instances of this attack: interruption of the master (P1-1) and outstation (P1-2).
- Transport Sequence Modification (P2):** The Sequence field is used to ensure in-order delivery of fragmented messages. The sequence number increments with each fragment sent, so predicting the next value is trivial. An attacker who inserts fabricated messages into a sequence of fragments can inject any data and/or cause processing errors. Table 2 lists eight instances of this attack: interruption of the master (P2-1) and outstation (P2-2); modification of the master (P2-3), outstation (P2-4) and network path (P2-5); and fabrication of the master (P2-6), outstation (P2-7) and network path (P2-8).

Table 3. Attack taxonomy for the DNP3 application layer.

<b>17 Attacks 48 Instances</b>	<b>Master</b>	<b>Outstation</b>	<b>Network</b>
<b>Interception</b>	C1-1 C3-1	C1-2 C3-2 A2-1 A14-1	C1-3 C3-3
<b>Interruption</b>	C2-1 C3-4 A10-1 A11-1 A12-1 A13-1	C2-2 C3-5 A1-1 A2-2 A3-1 A4-1 A5-1 A6-1 A7-1 A8-1 A9-1	C3-6
<b>Modification</b>	C2-3 C3-7 A10-2 A11-2 A12-2 A13-2	C2-4 C3-8 A1-2 A3-2 A4-2 A5-2 A6-2 A7-2 A8-2 A9-2	C3-9
<b>Fabrication</b>	C2-5 C3-10	C2-6 C3-11	C3-12

#### 4.4 Application Layer Attacks

The application layer provides the majority of functionality for DNP3 systems; consequently, the largest number of attacks are associated with this layer. The taxonomy in Table 3 lists seventeen attacks (including the three common attacks) and 48 attack instances (including 21 instances for the common attacks). Attacks on confidentiality obtain information about network topology, system configuration and functionality. Integrity attacks modify communication paths, provide bad data to the master and outstation devices, or reconfigure outstation devices. Availability attacks may cause devices to lose key functionality, reboot or crash. We discuss five attacks in more detail.

- **Outstation Write Attack (A3):** This attack sends a DNP3 message with Function Code 2, which writes data objects to an outstation. The attack can corrupt information stored in the outstation’s memory, causing an error or overflow. Table 3 lists two instances of this attack: interruption (A3-1) and modification (A3-2) of an outstation.
- **Clear Objects Attack (A4):** This attack sends a DNP3 message with Function Code 9 or 10 to freeze and clear data objects. The attack can clear critical data or cause an outstation device to malfunction or crash. Note that the attack involving Function Code 10 is problematic because a message with this function code does not require an acknowledgement. Table 3 lists two instances of this attack: interruption (A4-1) and modification (A4-2) of an outstation.
- **Outstation Data Reset (A6):** This attack sends a DNP3 message with Function Code 15. The attack causes an outstation device to reinitialize data objects to values inconsistent with the state of the system. Table

3 lists two instances of this attack: interruption (A6-1) and modification (A6-2) of an outstation.

- **Outstation Application Termination (A7):** This attack sends a DNP3 message with Function Code 18, which is used to terminate applications running on outstations. A message with this function code causes a device to become unresponsive to normal requests from the master. Table 3 lists two instances of this attack: interruption (A7-1) and modification (A7-2) of an outstation.
- **Configuration Capture Attack (A14):** This attack sends a message with the fifth bit in the second byte of the IIN set, which indicates that the configuration file of the targeted outstation is corrupted. The attack causes the master to transmit a new configuration file, which is intercepted by the attacker. A separate attack is then executed to modify and upload the file to the targeted outstation. Table 3 lists the one instance of this attack: interception of outstation data (A14-1).

Table 4. Impact of attacks on target assets.

<b>28 Attacks 91 Instances</b>	<b>Master</b>	<b>Outstation</b>	<b>Network</b>
<b>Interception</b>	2 Obtain Master Data	4 Obtain Outstation Data	2 Obtain Network Data
<b>Interruption</b>	14 DoS Master	20 DoS Outstation	5 DoS Network
<b>Modification</b>	11 Bad Data in Master	15 Bad Data in Outstation	4 Reconfigure Network Path
<b>Fabrication</b>	5 Control Process	5 Fabricate Outstation	4 Fabricate Network Path

## 5. Attack Impact

Table 4 summarizes the overall impact of the attacks on control system assets. Eight attack instances intercept device configuration data, process data and network information. Additionally, 39 attack instances result in denial of service (DoS); fourteen instances impact the master, twenty impact outstation devices and five impact network resources. Modification attacks insert erroneous data in devices, which affects the integrity of the control system. Eleven attack instances insert bad data in the master, fifteen in outstation devices, and four affect network paths. Fabrication attacks are particularly dangerous. Five attack instances enable an attacker to spoof outstation devices and four attack instances fabricate network paths. Most alarming are the five attack instances that spoof the master and seize partial or complete control of the process.

Table 5. Impact of attacks on control objectives.

	<b>Data Link Layer</b>	<b>Pseudo- Transport Layer</b>	<b>Application Layer</b>	<b>Common (All Layers)</b>
<b>Loss of Confidentiality</b>	0(0)	0(0)	2(2)	6(2)
<b>Loss of Awareness</b>	33(9)	10(2)	25(13)	15(2)
<b>Loss of Control</b>	29(9)	7(2)	25(13)	13(2)

Table 5 clarifies the impact of the attacks with respect to the principal industrial control system objectives of process confidentiality, process awareness and process control. Loss of confidentiality occurs when important information about device configuration or network topology is obtained by an attacker. Generally, this is the first step of a more serious attack, where reconnaissance is conducted to identify weaknesses and entry points. Loss of awareness occurs when the control center does not have accurate information about system status. For example, an attacker can trip a circuit breaker and prevent an alarm from reaching the operator. Such attacks can lead to serious incidents because their effects may go unnoticed until it is too late. Even more dangerous are the attacks that result in the loss of control – an attacker who usurps control of a SCADA master can potentially wreak havoc. Table 5 lists the numbers of attack instances and distinct attacks (in parentheses) that impact the three control system objectives. For example, two application layer attack instances (two attacks) result in a loss of confidentiality, and thirteen common attack instances (two common attacks) result in loss of control.

## 6. Conclusions

Our detailed analysis of the DNP3 protocol layers with respect to threats and targets has identified 28 attacks and 91 attack instances. The effects of the attacks range from obtaining network or device configuration data to corrupting outstation devices and seizing control of the master unit. It is important to note that our analysis, while detailed, is by no means comprehensive. In fact, we believe that many more attacks remain to be discovered. Most surprising is the large proportion of high-impact attacks, especially those involving the interruption, modification and fabrication of control system assets.

We hope that our work will stimulate efforts focused on analyzing SCADA protocols and characterizing cyber attacks on the electrical power grid. The results will contribute to the security of existing critical infrastructure assets as well as the design of next generation SCADA systems that are secure, reliable and resilient.

## References

- [1] G. Clarke and D. Reynolds, *Practical Modern SCADA Protocols: DNP3, IEC 60870.5 and Related Systems*, Newnes, Oxford, United Kingdom, 2004.
- [2] K. Curtis, A DNP3 Protocol Primer (Revision A), DNP3 Users Group, Calgary, Canada ([www.dnp.org/About/DNP3%20Primer%20Rev%20A.pdf](http://www.dnp.org/About/DNP3%20Primer%20Rev%20A.pdf)), 2005.
- [3] DNP Users Group, Pasadena, California ([www.dnp.org](http://www.dnp.org)), 2008.
- [4] Electric Power Research Institute, DNP Security Development, Evaluation and Testing Project Opportunity, Palo Alto, California ([my-docs.epri.com/docs/public/000000000001016988.pdf](http://my-docs.epri.com/docs/public/000000000001016988.pdf)), 2008.
- [5] P. Huber and M. Mills, Brawn and brains, *Forbes*, September 15, 2003.
- [6] P. Huitsing, R. Chandia, M. Papa and S. Shenoi, Attack taxonomies for the Modbus protocols, *International Journal of Critical Infrastructure Protection*, vol. 1, pp. 37–44, 2008.
- [7] Institute for Security Technology Studies, Cyber Security of the Electric Power Industry, Dartmouth College, Hanover, New Hampshire ([www.ists.dartmouth.edu/library/218.pdf](http://www.ists.dartmouth.edu/library/218.pdf)), 2002.
- [8] J. Meserve, Mouse click could plunge city into darkness, experts say, *CNN.com* ([www.cnn.com/2007/US/09/27/power.at.risk/index.html](http://www.cnn.com/2007/US/09/27/power.at.risk/index.html)), September 27, 2007.
- [9] C. Pfleeger and S. Lawrence-Pfleeger, *Security in Computing*, Prentice Hall, Upper Saddle River, New Jersey, 2007.
- [10] M. Smith, DNP V3.00 Transport Functions, DNP Users Group, Pasadena, California, 1992.
- [11] M. Smith and J. McFadyen, DNP V3.00 Application Layer Protocol Description, DNP Users Group, Pasadena, California, 1991.
- [12] M. Smith and J. McFadyen, DNP V3.00 Data Link Layer Protocol Description, DNP Users Group, Pasadena, California, 2000.
- [13] Sun Microsystems, Secure Enterprise Computing with the Solaris 8 Operating Environment, Palo Alto, California ([www.sun.com/software/whitepapers/wp-s8security/wp-s8security.pdf](http://www.sun.com/software/whitepapers/wp-s8security/wp-s8security.pdf)), 2000.
- [14] M. Thesing, DNP3 Specification Volume 7: IP Networking, DNP Users Group, Pasadena, California, 1998.
- [15] Triangle MicroWorks, DNP3 Overview, Raleigh, North Carolina ([www.trianglemicroworks.com/documents/DNP3\\_Overview.pdf](http://www.trianglemicroworks.com/documents/DNP3_Overview.pdf)), 2002.