Control System Data Authentication and Verification Using Elliptic Curve Digital Signature Algorithm

By

Kenneth Alan Fischer

Control System Data Authentication and Verification Using Elliptic Curve Digital Signature Algorithm

By

Kenneth Alan Fischer

Independent Study
Submitted to Department of Electrical and Computer Engineering
College of Engineering
Villanova University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

In

Computer Engineering

July, 2012

Villanova, Pennsylvania

Control System Data Authentication and Verification Using Elliptic Curve Digital Signature Algorithm

By

Kenneth Alan Fischer

Approved: _____

Dr. Richard Perry
Professor, Department of Computer and Electrical Engineering
Primary Advisor

Approved: _____

Dr. Pritpal Singh
Chair, Department of Computer and Electrical Engineering

STATEMENT BY AUTHOR

This independent study has been submitted in partial fulfillment of requirements for an advanced degree at the Villanova University.

Brief quotations are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Associate Dean for Graduate Studies and Research of the College of Engineering when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

ACKNOWLEDGEMENTS

This independent study is the result of my M.Sc studies at Villanova University. Firstly, I would like to thank my advisor, Dr. Richard Perry, for sharing his time, experience, and wisdom during my research. I would also to thank my supervisor, Michael Iacovelli (NSWCCD-SSES C955 Branch Manager) for his support in enabling me to pursue this work, as well as all of my colleagues within NSWCCD-SSES who took the time to listen to my ideas and share with me their own insight and practical experience in the field of Control System Engineering. Lastly and most importantly, I would like to thank my wife, Ana Fischer, for all the extra work she did in taking care of our two year old daughter while I pursued this work.

DEDICATION

I dedicate this independent to my daughter Liviya,

Whose insatiable curiosity in the world

Inspires me to learn daily

And to the men and women of our armed forces

Who deserve our best

As they defend us around the world.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ALGORITHMS

ABSTRACT

Recent endeavors such as the Smart Grid and the Navy's Next Generation Integrated Power System, along with attacks on control systems such as Stuxnet, have highlighted the need for improved security in control systems and control system communications. Control system components such as Programmable Logic Controllers (PLCs) and Human-Machine Interfaces (HMIs) can no longer rely on simple heartbeat logic algorithms in order to verify communications. We can no longer rely on parity and checksum algorithms to determine that messages are coming through intact and unmodified. Advanced cryptographic algorithms for data authentication and verification are needed in messaging protocols between PLCs, HMIs, and sensors.

Cryptographic algorithms such as RSA or the Digital Signature Algorithm (DSA) appear to provide a solution to this need on the surface. A deeper look though reveals that the key sizes required for implementing these solutions are simply not feasible for implementation in control system equipment. Elliptic Curve DSA (ECDSA) looks to be a promising solution due to the smaller key sizes which allow for smaller storage requirements and faster computations (except in signature verification). The implementation of ECDSA can be complicated, but techniques such as the NIST prime fields can greatly increase the efficiency of the algorithm for use in control systems.

Before a full control system implementation of ECDSA should be developed, the use of existing implementations such as those found in OpenSSL can be used with SoftPLCs to develop a proof of concept. This will allow us to study the effects of using ECDSA on control system performance, as well as to develop a more complete set of user requirements for a complete control system solution that will be easy to implement.

CHAPTER 1: INTRODUCTION

1.1 Background

Increasing demands in all sectors of an industrial society have led to an ever increasing need for more sophisticated controls and monitoring equipment and software. Control systems, once consisting of simple transmitters and relays have evolved into complex systems containing dozens of controllers communicating with each other, each containing tens of thousands of lines of code, for even the simplest processes. Complex Human-Machine Interface (HMI) mechanisms designed to give system owners and operators enhanced capabilities to remotely operate, maintain, and troubleshot equipment are being developed and deployed. At the core of most modern control systems is the Programmable Logic Controller (PLC), a device whose power lies in the ability of a Control System Engineer to quickly and easily implement complex control schemes at minimal cost. As a result, PLCs (originally designed to replace relay panels) have become prevalent in virtually every industrial environment from pharmaceutical plants to electrical power distribution systems.

The need for PLCs will significantly expand in the coming years, as countries with mature economies work tirelessly to develop new sophisticated power distribution networks required to support our growing economy. Our existing power grids were designed decades ago, with the main aim of delivering electricity from large power stations to households and businesses. The increasing efficiency and reliable requirements necessary to support our developing civilization in the face of increasing energy demands and the real threat of domestic terrorism and foreign aggression require

significant modernization of these power distribution networks. The new “Smart Grid”, as it commonly called, will be characterized by a two-way flow of electricity and information creating a widely distributed energy network. The control system required to support this energy network will be of an unheard of scale, the design of which will introduce significant challenges never before addressed.

In related efforts, the US Navy has been rapidly migrating to ship designs with propulsion, auxiliary, and weapons systems with significantly higher energy requirements than in the past. To address these requirements, modern ship designs such as the USS ZUMWALT DESTROYER (DDG1000) class are using Integrated Power Systems (IPS) that provide electrical power to propulsion and electrical loads from a common set of sources. To provide direction for future IPS development, the Navy initiated the Next Generation Integrated Power Systems (NGIPS) effort to provide smaller, simpler, more affordable, and more capable systems for all Navy ships.

The NGIPS effort is remarkably similar to the Smart Grid effort in multiple respects, and in both there is an increasing consensus that the controls communication infrastructure needs fundamental changes. In an automated electrical system, damage to a complex communication network, a hostile terrorist act, or even a failing component giving erroneous data can result in a control system taking improper actions that could result in large scale power failures on land and weapons, propulsion, or a complete electrical failure at sea or worse. Earlier this year, we at NSWCCD-SSES documented a case where erroneous data from a failing control system communications component in an Improved Navy Lighterage System (INLS) Warping Tug (WT) resulted in a complete loss of propulsion and steering control whenever a ship was placed into full speed, which

would have resulted in the ship colliding into the shore if it were not for conveniently placed Emergency Stop pushbuttons. It has become clear to controls engineers that more sophisticated methods are needed for verifying the integrity of the data and commands being issued to and from control systems.

Implementing control systems on a large, highly integrated scale introduces significant challenges partly because control system networks were not designed with security being primarily in mind. Historically, control system networks were designed to be completely physically isolated from other networks and therefore securing those control system networks seemed unnecessary. Instead, control system networks were designed to have maximum throughput with minimal to nonexistent data loss. In recent years though control systems have gradually been getting connected to the Internet, mostly via corporate network systems, in order to meet business and maintenance requirements. In order to secure networks, IT administrators have been applying traditional security measures in order to prevent attackers from gaining access to the corporate networks thus protecting control system networks. The last year particularly has highlighted the deficiencies with this model, as viruses such as Stuxnet have become rapidly prevalent. There is also significantly more risk in a compromised control system than a compromised corporate system. For example, an attacker could compromise the control system of a nuclear power plant resulting in a failure of the reactor cooling system. Therefore control system designers are realizing that not only do we need improved algorithms to verify that control system data is accurate, we need algorithms to verify that the data and commands to the control systems are authenticated (i.e. coming from a valid, recognized source).

1.2 Current Practices

Controls engineers have long recognized the need to verify that components within a control system are communicating, and that the failure of communications between control system components should result in critical high priority alarms with possible equipment shutdowns. Since control system communications operate in real time, 24 hours a day, 7 days a week, algorithms are needed to detect a failure in communications as soon as it occurs. Traditionally, "heartbeat" logic is implemented between each pair of communication devices. Algorithm 1.1.A below illustrates an example of commonly used "heartbeat" logic.

Algorithm 1.1.A – Traditional Control System "Heartbeat"

1. Initialize a bit to a known condition (typically 1 as will be used in this algorithm).
2. Transmit bit (call it B1) to communication partner. Start a 3 second timer (call it T1)
3. Communication partner receives the bit B1. Communication partner sets another bit (call it B2) to 1 to match the state of B1 and starts its own 3 second timer (call it T2).
4. Receive bit B2 from the partner. Verify that the state of B2 matches the state of B1 and that timer T1 has not timed out. If true, restart timer T1. Change state of B1 to be opposite that of B2. Transmit B1 back to partner.

5. Partner receives bit B1. Partner verifies that the state of B1 does not match the state of B2 and that timer T2 has not timed out. If true, partner restarts timer T2. Partner changes B2 to match state of B1, retransmits bit back, and go to step 4.
6. If T1 or T2 times out, alarm for communications failure.

As long as a communications failure alarm does not occur, then the data being transmitted between the two PLCs is considered to be both valid and sourced between the communicating pair. This kind of logic has proven to be very effective for general network health monitoring. Issues in communication, primarily in the physical or transport layer, can be easily detected using this method. For control system networks that are physically isolated from any other network, this is generally sufficient to implement an effective control scheme. Unfortunately, this method does not protect against any kind of more sophisticated failure or attack such as that documented for the INLS WT described earlier or a "man-in-the-middle" attack.

1.3 Literature Review on Smart Grid

A number of papers have been written to introduce the Smart Grid concepts and provide a general overview of the requirements and challenges involved in developing a Smart Grid.

Bouhafs, Mackay, and Merabti (2012) [1] identified a number of general requirements including communications and electrical generation needed in order to fully realize the Smart Grid vision. They noted that underlying communications protocols will need to be more flexible and enable horizontal data exchange between controllers and remote

terminal units (RTUs). The current "heartbeat" logic concept would not be useful in an implementation where data could flow from a source through multiple sources to a target since it only verifies the link between pairs and not the data itself. They went on to note that in the event the Internet is used to connect equipment in the Smart Grid strong encryption and authentication measures must be taken to ensure the security of the data in transit.

Yan, Qian, Sharif, and Tipper (2012) [2] noted that it is necessary to have guaranteed Quality of Service (QoS) for the communications and networking technology. In particular they highlighted latency, bandwidth, interoperability, scalability, and security requirements. Of particular interest is the authors analysis of bandwidth requirements which showed that there will be significant challenges in this area. Therefore, adding a significant number of bits in any communications protocol for control systems could have a profoundly negative impact on the operation of the Smart Grid as a whole. The authors also noted that the effort required to provision symmetric keys (i.e. keys between each pair of communicating devices) into thousands of devices would be too expensive or insecure. They noted that the development of key and trust management schemes for large network deployments would be required. While Navy systems are small enough that they would not suffer from the same kinds of limitations, it seems obvious that a solution must be developed for Navy systems that would be applicable to all future controls systems including the Smart Grid, particularly in support of modernized shore power connections for Navy systems.

Yan, Qian, Sharif, and Tipper (2012) [3] in a related paper noted that new functions in the Smart Grid such as demand response introduce significant new cyber attack vectors

such as a malware that initiates a massive coordinated and instantaneous drop in demand. This attack could result in substantial damage to distribution, transmission, and generation facilities. Research ongoing at NSWCCD-SSES has also noted this risk as applicable to Navy systems, particularly in combat scenarios with the use of advanced weapon systems such as the railgun. The authors also noted that a major difference between Smart Grid controls communication and the Internet is that the controls data is significantly more concerned with message delay and timing constraints.

Liu, Ning, and Reiter (2009) [4] in their work presented a notable example of a new type of attack, called false data injection attacks, that highlights the very real risk of attacks targeting data integrity.

Baumeister (2011) [5] noted that most information systems uses a Public Key Infrastruction (PKI) solution, but that the nature of power grid systems creates additional PKI requirements not present in traditional information systems. This same statement can be generalized to apply to all control systems. For example, Baumeister noted that control systems must make informed decisions regularly, and that it is unreasonable to expect a control system to go down or revert to a less efficient predecessor every time a certificate is unavailable. For example, what happens when a certificate from a sensor expires? In an information system, the impact of expired certificates is insignificant and they can be renewed when discovered. However, in a control system this could cause the process (such as electric flows) to be incorrectly altered.

1.3.1 SGiP Cyber Security Working Group NISTIR 7628

In response to the number of concerns related to the Smart Grid and Cyber Security, NIST established the Smart Grid Interoperability Panel (SGiP) Cyber Security Working Group which published NISTIR 7628 (2010) [6]. This document broke down the various kinds of communications that would be prevelant in a full international Smart Grid system into a number of categories such as "Category 10 – Interface between Control Systems and Non-Control / Corporate Systems". SGiP then identifies the unique security requirements for each of these categories, focusing on the three areas of confidentiality, integrity, and availability. Most, but not all of the categories identified by SGiP are directly or indirectly applicable to control systems (some have little to no bearing such as categories 13 through 18) operating in the Smart Grid and are shown in the list below:

- Category 1: Interface between control systems and equipment with high availability, and with compute and/or bandwidth constraints
- Category 2: Interface between control systems and equipment without high availability, but with compute and / or bandwidth constraints
- Category 3: Interface between control systems and equipment with high availability, without compute or bandwidth constraints
- Category 4: Interface between control systems and equipment without high availability, without compute or bandwidth constraints
- Category 5: Interface between control systems within the same organization
- Category 6: Interface between control systems in different organizations
- Category 10: Interface between control systems and non-control / corporate systems

- Category 12: Interface between sensor networks and control systems
- Category 19: Interface between operations decision support systems
- Category 20: Interface between engineering / maintenance systems and control equipment
- Category 21: Interface between control systems and their vendors for standard maintenance and service
- Category 22: Interface between security / network / system management consoles and all networks and systems

In reviewing the categories, it becomes obvious that all of them have significant overlap with NGIPS efforts as well as industrial control systems in general. Going through the requirements of these categories as identified by SGiP it is seen that the primary concern in this categories that of data integrity and authentication. Data encryption can be useful in some circumstances, but is not as critical as the other two requirements.

1.4 Literature Review on NGIPS

Most of the literature focusing on the NGIPS effort has focused on areas such as electrical generation, propulsion, power conversion and distribution, energy storage, and zonal survivability. NAVSEA (2007) [7] The NGIPS architecture is broken up into seven modules types:

- Power Generation Modules (PGM)
- Power Distribution Modules (PDM)
- Power Conversion Modules (PCM)
- Energy Storage Modules (ESM)

- Power Loads
- Propulsion Motor Modules (PMM)
- Power Control Modules (PCON)

The PCON module is of particular interest to controls engineers, as it consists of the software and communications protocols necessary to operate the system. Doerry (2009) [8] noted that PCON should implement the following functions, and that the software should be developed for robustness in anticipation of future changes in the life of both a ship and for modifying for use across multiple ship classes:

- Remote monitoring and control of NGIPS modules and controllable loads
- Resource Planning
- System Configuration
- Mission Priority Load Shedding
- Quality of Service Load Shedding
- Fault Detection and Isolation
- Maintenance Support
- Training

These functions are remarkably similar to the control system functions required for the development of a Smart Grid, with the notable exception of Quality of Service (QoS) and Mission Priority Load Shedding. As a result, the same need for data authentication and verification in the Smart Grid would be applicable to NGIPS, particularly in functions such as maintenance support where it becomes increasingly common for ships to transmit data to and from shore based services for software upgrades and maintenance / troubleshooting support.

Desired requirements for QoS also introduce the need to ensure that commands being transmitted across the ship for electrical service are genuine. As noted by Doerry, a typical cause of a QoS failure is the shifting of electrical power sources from ship to shore, and that communications will be required with the terrestrial power system command and control centers. Failure of the ship and shore to properly establish valid communications could result in power instabilities for both.

The increasing prevalence of computer viruses specifically targeting control systems will introduce new challenges to the mission readiness of a ship in times of war. By attacking PCON, an enemy may be able to cause a control system to incorrectly transfer loads which could result in a failure of propulsion or weapon systems (or both) at a critical moment. Modern weapon systems produce substantial electrical loads that may require realigning of the ship's electrical distribution prior to being operational.

The Navy has been putting in significant effort to develop open architecture approaches in the development of control system software to support not only NGIPS development but also to support development of control systems fleet wide. Doerry, Scherer, Cohen, and Guertin (2011) [9] pointed out that information assurance and security needs to be thought of at the outset of any new MCS design, stating that confidentiality, integrity, and availability of data must be assured. They also highlight that the software should perform error detection (and error correction if possible) along with filtering of the sensor data.

CHAPTER 2: CURRENT PRACTICES

2.1 Fundamental Objectives

Within the field of cryptography there are multiple solutions providing various degrees of secure communication. In order to be effectively used to establish secure communications these solutions have the following fundamental objectives:

- Confidentiality – ensuring the data can only be read by those authorized to see it
- Data Integrity – ensuring the data has not been modified by unauthorized means
- Data Origin Authentication – ensuring data supposedly sent by a source actually originated with that source
- Entity Authentication – ensuring that an entity participating in a data transfer is who it claims to be
- Non-repudiation – ensuring that a source of data is unable to later deny sending the data

Information / Corporate systems are concerned with meeting each of the above objectives. Control systems are also equally concerned with these, with confidentiality to a significantly lesser degree, but also have unique requirements not present in information systems. When an information system receives a piece of data through an unsecure means you can disregard the information with reasonably low risk. Control systems, on the other hand, need to make critical decisions with the information at hand. If the data received is insecure, the control system is placed in a position of having to make critical decisions about the operation of real world machinery without knowing which decision to take. Unfortunately, the control system will regularly be in the

position where it must take some critical action or shut down the equipment, with each scenario resulting in possible equipment damage and injury/death to personnel operating that equipment.

2.2 Limitations of Control Systems compared to Information / Corporate Systems

Information / Corporate Systems will typically consist of x86-based architecture computers running either Windows or Linux operating systems and a host of other software programs provided by multiple vendors to provide an integrated solution. At the heart of the Control System are Programmable Logic Controllers (PLCs), which use vendor specific developer environments to write software following IEC 61131-3 guidelines (ladder logic, function blocks, etc) to implement a solution that is both easy and cheap to design and is very effective for controls. The downside of these PLCs is that they tend to have significantly less processing power and storage capabilities as they are designed to run very specific software programs extremely efficiently, non-stop, for 20 years or more.

An alternative to PLCs are VERSAmodule Eurocards (VME) which tend to have greater processing power and contain the same input / output processing capabilities as PLCs but add significant complexity to the design of a control system. The pros and cons of PLCs and VMEs are described below. Another alternative to PLCs are SoftPLCs. SoftPLCs are essentially programmed in the same manner as regular PLCs, but contain additional underlying base code designed to interface with an operating system (typically Windows NT based operating systems) in order to run the IEC 61131-3 code on an x86-based

architecture. Figures 2.2A and 2.2.B are of running PLC and VME racks on control systems for Navy Ships

Figure 2.2.A PLC Rack

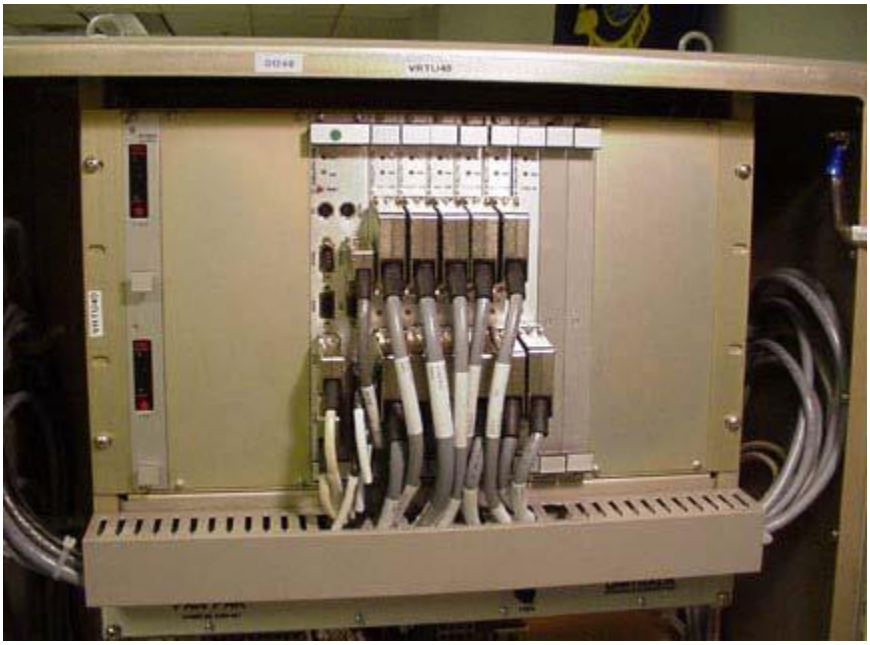


Figure 2.2.B VME Rack

Since VME cards can be obtained that use the x86 architecture, in recent years the Navy has been implementing control systems on ship classes that use SoftPLCs running on VMEs to obtain the best of both worlds. This can be a complicated and expensive solution that is still more in the research and development stage and will likely not be implemented in either the Smart Grid or regular industrial control systems. However it is possible from a research perspective to perform cryptography testing on SoftPLCs using VMEs to do "proof of concept" testing in order to determine the validity of a solution before expending significant resources in developing an independent and complete PLC solution.

2.2.1 PLC versus VME

In order to give greater perspective on the usage of PLCs versus VMEs in control systems, the pros and cons of both technologies are listed below. These SoftPLCs may become more prevalent in industrial control systems with the advent of new projects such as OpenPLC which aims to develop an open source software and hardware platform for industrial control systems.

VME Pros

- Analog and digital I/O boards are available from a large number of vendors
- VME components are open architecture
- Standardized circuit card form factor and data bus

- Significantly greater flexibility in software for VME than compared to PLC, allowing for advanced processing not available with PLCs (such as required for the DDG1000)
- Ability to implement secure communication protocols
- Operating Temperature of -40^{o}C to +85^{o}C

VME Cons

- Development of software is complex and difficult, developer must design not only the control system application but also the low-level system interactions
- Widespread use of proprietary operating systems often creates a virtual sole-source situation
- Instability in VME Operating System market means it is unlikely developers will have experience with the operating system chosen for a new project, leading to longer ramp-up time and increased risk for software defects
- Obsolescence is a major problem
- Integration of new components into an existing system is NOT “plug-and-play”

PLC Pros

- Cost is less than for VME systems
- Programming time is reduced due to ease of programming language (ladder-logic)
- Risk is significantly reduced when using all products from the same vendor
- Integration of new components into an existing system is typically “plug-and-play”

- PLC vendors have a strong record of supporting their products for 20 years or longer
- Enhanced software troubleshooting features not available with VMEs

PLC Cons

- PLC vendor products generally not compatible with another vendor's products, requiring a single vendor to provide all processor, I/O, and network communication boards
- No standards for PLC form factor or electrical characteristics
- Secure communication protocols are not a common feature with many PLC vendors
- Increased risk in relying on a single vendor to support their products
- Operating Temperature of 0^{o}C to $+60^{o}$C

2.3 Traditional Solutions for Information / Corporate Systems

While traditional solutions for Information / Corporate Systems will not be feasible for implementation in Control Systems due to the different requirements and architectures, it is important to establish an understanding of current solutions used in Information Systems. There are essentially two main categories of cryptographic solutions, symmetric-key cryptography and public-key cryptography.

2.3.1 Symmetric-key Cryptography

Symmetric-key Cryptography includes schemes such as the Data Encryption Standard (DES) (now obsolete), RC4, and the Advanced Encryption Standard (AES) to achieve confidentiality. They may also be used with a message authentication code (MAC) algorithm such as HMAC to achieve data integrity and data origin authentication. In a typical symmetric-key cryptography scheme two parties already share a secret key k that has been communicated to the parties by some other means (typically a physical secure channel such as a trusted courier, or by using a public-key cryptography scheme to negotiate a shared secret key). Party A wishing to transmit to B uses one of the previously mentioned schemes to compute a ciphertext $c = ENC_k(m)$ to be sent to B. B then receives the message and using the same k (and knowing the same scheme used to encrypt m used by A) to recover the plaintext message $m = DEC_k(c)$.

If data integrity and data origin authentication are desired, then the same principles apply however instead of encrypting the message m into ciphertext c a tag t is first computed where $t = MAC_k(m)$ of the plaintext message using a MAC algorithm (of which there are many) and the key. The plaintext message and the tag are both transmitted, and the receiver can use the plaintext message to compute its own tag t'. If $t = t'$ then the receiver can accept the message as having originated from the source.

While symmetric-key cryptography can be very efficient, the key distribution and key management problems tend to render it ineffective for large scale systems communicating to multiple partners [10]. In a network of N entities, each entity may have to maintain keying material with each of the other $N-1$ entitites. Some symmetric-key systems attempt to alleviate this problem by using an online trusted third party that

distributes the keys as required, however for control systems this creates a single critical point of failure that will be unacceptable as control systems become more and more distributed and de-centralized. Additionally, while key distribution in symmetric-key cryptography may be possible through a physical courier on a ship (for NGIPS) it will not be practical for large scale systems such as the Smart Grid.

2.3.2 Public-key Cryptography

Public-key cryptography began in 1975 to address the aforementioned limitations in symmetric-key cryptography. Unlike symmetric-key schemes, public-key schemes require the keying material that is exchanged to only be authentic, but not secret. Additionally, instead of each pair of entities sharing a secret key, each entity selects a single pair of keys *(e, d)* consisting of a *public key e* and a related *private key d*. The entity keeps the private key a secret from all other entities and shares the public key with all other entities. The keys are mathematically related but share the property that it is computationally infeasible to determine the private key solely from knowledge of the public key. Deriving the private key from the public key is equivalent to solving a computational problem that is believed to be intractable.

2.3.2.1 RSA

The most commonly used public-key cryptography scheme is RSA, named after its inventors Rivest, Shamir, and Adleman [11]. It was first proposed in 1977 shortly after the discovery of public-key cryptography. In RSA, the public key consists of a pair of integers *(n, e)* where *n* is the modulus. The modulus is a product of two randomly

generated (and secret) primes p and q which are of the same bitlength. Algorithm 2.3.2.1.A below shows how to generate an RSA key pair. RSA encryption and signature schemes use the fact that $m^{ed} = m \pmod{n}$. Algorithms 2.3.2.1.B and 2.3.2.1.C show how basic RSA encryption and decryption work respectively. The hardness in breaking RSA is based on the integer factorization problem, i.e. determining the secret primes p and q from the public key for large values of bitlength l.

The RSA signature generation and signature verification algorithms are shown in algorithm 2.3.2.1.D and 2.3.2.1.E. As in all signature schemes, the signer first generates a cryptographic hash function H which acts in a similar manner as the tag in symmetric-key encryption. The signer then generates the signature and transmits the message m along with the signature s to a verifying party.

In order to increase the efficiency of RSA, smaller exponents can be selected. In practice, the most commonly chosen values of e are $e = 3$ and $e = 65537$ for encryption and signature generation [11]. Note that there is no known attack against using small public exponents as long as proper padding is used. Decryption and signature generation always use the exponent d (the private key) which is the same bitlength as n. Thus RSA encryption and signature verification with small values of e are significantly faster than RSA decryption and signature generation.

Algorithm 2.3.2.1.A [10] – Generating RSA Key Pair

INPUT: bitlength l

OUTPUT: RSA public key (n, e) and private key d

1. Randomly select two primes p and q of the same bitlength $l / 2$

2. Compute n = pq and $\Phi = (p-1)(q-1)$
3. Select an arbitrary integer e with $1 < e < \Phi$ and $gcd(e, \Phi) = 1$
4. Compute the integer d satisfying $1 < d < \Phi$ and $ed \equiv 1 \pmod{\Phi}$
5. Return (n, e, d)

Algorithm 2.3.2.1.B [10] – RSA Encryption

INPUT: RSA public key (n, e), plaintext $m \in [0, n-1]$

OUTPUT: Ciphertext c

1. Compute $c = m^e \bmod n$
2. Return (c)

Algorithm 2.3.2.1.C [10] – RSA Decryption

INPUT: RSA public key (n, e), RSA private key d, ciphertext c

OUTPUT: Plaintext m

1. Compute $m = c^d \bmod n$
2. Return (m)

Algorithm 2.3.2.1.D [10] – RSA Signature Generation

INPUT: RSA public key (n, e), RSA private key d, message m

OUTPUT: Signature s

1. Compute $h = H(m)$ where H is a cryptographic hash function
2. Compute $s = h^d \bmod n$
3. Return (s)

Algorithm 2.3.2.1.E [10] – RSA Signature Verification

INPUT: RSA public key *(n, e),* message *m,* signature *s*

OUTPUT: Acceptance or rejection of the signature

1. Compute $h = H(m)$ where H is the same cryptographic hash function used by the signing party
2. Compute $h' = s^e \bmod n$
3. If $h = h'$ then accept the signature, else reject

2.3.2.2 Digital Signature Algorithm

In 1976 Diffie and Hellman proposed developing a key agreement protocol based on the discrete logarithm problem (DLP) [10], which like the integer factorization problem used in RSA is computationally infeasible to solve. Discrete logarithms are group-theoretic analogues of ordinary logarithms. For example, an ordinary logarithm $log_a(b)$ is a solution of the equation $a^x = b$ for x. In a discrete logarithm, you have a group G which consists of a range of integer values from 0 to n-1. If a and b are elements in the group then a solution of x of the equation $a^x = b$ is called a discrete logarithm to the base a of b in the group G. In a discrete logarithm public-key cryptography system a key pair is associated with a set of domain parameters (p, q, g). Algorithm 2.3.2.2.A shows how these domain parameters are generated, and Algorithm 2.3.2.2.B shows how to generate corresponding key pairs.

In 1984 ElGamal described discrete logarithm public-key encryption and signature schemes, and since then many different variants have been proposed leading up to the

establishment of the Digital Signature Algorithm (DSA) [10]. DSA was proposed in August 1991 by the U.S. National Institute of Standards and Technology (NIST) and was specified in a U.S. Government Federal Information Processing Standard (FIPS 186), adopted in 1993. A minor revision was issued in 1996 as FIPS 186-1, which was expanded further in 2000 as FIPS 186-2 and again in 2009 as FIPS 186-3 [12]. Algorithms 2.3.2.2.C and 2.3.2.2.D shown below give the procedures respectively for DSA signature generation and verification.

Algorithm 2.3.2.2.A [10] – Discrete Logarithm Domain Parameter Generation

INPUT: Parameters l and t

OUTPUT: Discrete logarithm domain parameters (p, q, g)

1. Select a t-bit prime q and an l-bit prime p such that q divides $p-1$
2. Select an element g of order q
    a. Select arbitrary $h \in [1, p-1]$ and compute $g = h^{(p-1)/q} \bmod p$
    b. If $g = 1$ then repeat 2.a.
3. Return (p, q, g)

Algorithm 2.3.2.2.B [10] – Discrete Logarithm Key Pair Generation

INPUT: Discrete logarithm domain parameters (p, q, g)

OUTPUT: Public key y and private key x

1. Select $x \in_R [1, q-1]$
2. Compute $y = g^x \bmod p$
3. Return (y, x)

Algorithm 2.3.2.2.C [10] – DSA Signature Generation

INPUT: Discrete logarithm domain parameters *(p, q, g),* private key *x*, message *m*

OUTPUT: Signature *(r, s)*

1. Select $k \in_R [1, q-1]$
2. Compute $T = g^k \bmod p$
3. Compute $r = T \bmod q$, if $r = 0$ then go to step 1
4. Compute $h = H(m)$, where H is a cryptographic hash function
5. Compute $s = k^{-1}(h+xr) \bmod q$, if $s = 0$ then go to step 1
6. Return *(r, s)*

Algorithm 2.3.2.2.D [10] – DSA Signature Verification

INPUT: Discrete logarithm domain parameters *(p, q, g),* public key *y*, message *m*, signature *(r, s)*

OUTPUT: Acceptance or rejection of the signature

1. Verify that *r* and *s* are integers in the interval *[1, q-1]*, if either verification fails then reject the signature
2. Compute $h = H(m)$, where H is the same cryptographic hash function used by the signing party
3. Compute $w = s^{-1} \bmod q$
4. Compute $u_1 = hw \bmod q$ and $u_2 = rw \bmod q$
5. Compute $T = g^{u1} y^{u2} \bmod p$
6. Compute $r' = T \bmod q$

7. If $r' = r$ then accept the signature, else reject

2.3.2.3 Limitations Using Public-Key Cryptography

In cryptography, the security of an algorithm cannot exceed its key length (measured in bits) since any algorithm can be cracked by brute force. A key therefore should be sufficiently large enough such that a brute force attack is infeasible – i.e. it would take too long to execute. If there is some indicator that an attack may exist to feasibly break a key for a particular algorithm in an efficient manner for some bit length, then the size of the key is increased to provide additional security. The key size to security level ratio is not the same for all categories of algorithms.

As of 2003 [13] RSA Security claims that 1024-bit RSA keys are equivalent in strength to 80-bit symmetric keys, 2048-bit RSA keys to 112-bit symmetric keys and 3072-bit RSA keys to 128-bit symmetric keys. RSA claims that 1024-bit keys are likely to become crackable some time between 2006 and 2010 and that 2048-bit keys are sufficient until 2030. An RSA key length of 3072 bits should be used if security is required beyond 2030. NIST key management guidelines further suggest that 15360-bit RSA keys are equivalent in strength to 256-bit symmetric keys. These key lengths, while implementable in Information / Corporate systems, are infeasible in Control Systems where processing power and data storage is limited. Therefore an alternative public-key algorithm is needed that provides the benefits of algorithms such as RSA and DSA without the excessive key lengths required by these algorithms.

CHAPTER 3: ELLIPTIC CURVE CRYPTOGRAPHY

3.1 Background

Elliptic curve public key cryptosystems were first independently proposed by V.S. Miller (1985) [14] and by N. Koblitz (1987) [15]. They have only begun to recently be used in commercial systems, and adoption has been slow. This is primarily due to concerns about intellectual property, as a number of optimizations and special algorithms used to increase efficiency have been patented in recent years. Despite these concerns, elliptic curve cryptography (ECC) has grown resulting in its inclusion in standards by accredited standards organizations such as ANSI (American National Standards Institute) [16, 17], IEEE (Institute of Electrical and Electronics Engineers) [18], ISO (International Standards Organization [19, 20], and NIST (National Institute of Standards and Technology [21].

The most prominent group for the standardization and propagation of ECC technology is SECG (Standards for Efficient Cryptography Group) [22]. They have published numerous and detailed works on the subject, including documents on how to implement ECC and on recommended elliptic curve domain parameters [23, 24]. The SECG consists of a number of organizations including NIST and key industrial partners such as VISA, Fujitsu, and Certicom. Certicom, which is a wholly owned subsidiary of Research in Motion (RIM) is the main industrial leader in ECC, with over 350 patents and patents pending worldwide covering key aspects of the technology [25].

In order to promote the use of ECC technology, NIST has licensed 26 patents held by Certicom with the right to grant sublicenses for free to industrial vendors for developing

products used for protecting national security information [6]. NIST has also identified a subset of key ECC technologies for use in Smart Grid and related applications, such as the Elliptic Curve Digital Signature Algorithm as part of its NSA Suite B collection of approved encryption, key exchange, digital signature, and hashing protocols. It is also worth noting that ECC implementation strategies based on the fundamental algorithms of ECC, which were published prior to filing dates of many patents can be found in the IETF Memo "Fundamental Elliptic Curve Cryptography Algorithms." [26]

3.2 Mathematical Foundations

This section presents an overview of the mathematical techniques and concepts required for an intermediary level of understanding of elliptic curve cryptography. This material is sufficient for engineering purposes to develop ECC systems using standardized existing mathematic implementations and standardized elliptic curve domain parameters. The works of Koblitz [15], Miller [14], Hankerson et al [10], and the SECG [23] can be referred to for more advanced mathematical concepts that may be helpful should the need arise for development of new implementations or the use of random elliptic curve domain parameters.

3.2.1 Finite Fields

A finite field $\mathbb{F}_{q^m}$ consists of a finite set of objects called field elements together with the description of two operations – addition and multiplication – that can be performed on pairs of field elements. Subtraction and division within a finite field are defined in terms of an additive inverse and multiplicative inverse, respectively. In ECC there are two

kinds of fields that are primarily used: prime finite fields $\mathbb{F}_p$ with $q=p$ and $m=1$, with q being prime; and binary fields $\mathbb{F}_{2^m}$ where $q=2$ for some $m \geq 1$. A third type of field less commonly used is known is Optimal Extension Fields (OEF). The general idea in OEFs is to select values of q and m, along with a reduction polynomial to more closely match underlying hardware characteristics [10]. At this time there are no recommended implementations of ECC by SECG that utilize OEFs, and therefore they are only mentioned here for completeness.

Equations involving finite fields do not explicitly denote the *mod p* operation, but it is understood to be implicit.

3.2.1.1 Prime Finite Fields [23]

Elements in a prime finite field $\mathbb{F}_p$ should be represented by the set of integers:

$$\{0, 1, \ldots, p-1\}$$

Operations on prime finite fields are defined as follows:

- Addition: If $a, b \in \mathbb{F}_p$, then $a + b = r$ in $\mathbb{F}_p$, where $r \in [0, p-1]$ is the remainder when the integer $a + b$ is divided by p.
- Multiplication: If $a, b \in \mathbb{F}_p$, then $ab = s$ in $\mathbb{F}_p$ where $s \in [0, p-1]$ is the remainder when the integer ab is divided by p.
- Additive inverse: If $a \in \mathbb{F}_p$, then the additive inverse $(-a)$ of a in $\mathbb{F}_p$ is the unique solution to the equation $a + x \equiv 0 \bmod p$.
- Multiplicative inverse: If $a \in \mathbb{F}_p$, $a \neq 0$, then the multiplicative inverse a^{-1} of a in $\mathbb{F}_p$ is the unique solution to the equation $ax \equiv 1 \bmod p$.

In order to increase efficiency and to facilitate interoperability, prime finite fields using the NIST primes should be use. These finite fields have:

$$[\log_2 p] \in \{192, 224, 256, 384, 521\}$$

Except for 521, p is aligned with word size to increase efficiency in computation and communication. 521 is an anomaly that is often included to align with the U.S. government's recommended elliptic curve domain parameters. For control systems with limited processing power and storage it is recommend to use only the NIST recommend primes that are aligned with word size such as 384.

3.2.1.2 Binary Finite Fields [23]

Elements of a binary finite field $\mathbb{F}_{2^m}$ should be represented by the set of binary polynomials of degree *m-1* or less:

$$\{a_{m-1}x^{m-1} + a_{m-2}x^{m-2} + \ldots + a_1 x + a_0 : a_i \in \{0,1\}\}$$

Operations on binary finite fields are defined as follows:

- Addition: If $a = a_{m-1}x^{m-1} + a_{m-2}x^{m-2} + \ldots + a_0$, $b = b_{m-1}x^{m-1} + b_{m-2}x^{m-2} + \ldots + b_0 \in \mathbb{F}_{2^m}$, then $a + b = r$ in $\mathbb{F}_{2^m}$ where $r = r_{m-1}x^{m-1} + r_{m-2}x^{m-2} + \ldots + r_0$ with $r_i \equiv a_i + b_i \bmod 2$
- Multiplication: If $a = a_{m-1}x^{m-1} + a_{m-2}x^{m-2} + \ldots + a_0$, $b = b_{m-1}x^{m-1} + b_{m-2}x^{m-2} + \ldots + b_0 \in \mathbb{F}_{2^m}$, then $ab = s$ in $\mathbb{F}_{2^m}$ where $s = s_{m-1}x^{m-1} + s_{m-2}x^{m-2} + \ldots + s_0$ is the remainder when the polynomial ab is divided by $f(x)$ with all coefficient arithmetic performed modulo 2.
- Additive inverse: If $a \in \mathbb{F}_{2^m}$, then the additive inverse ($-a$) of a in $\mathbb{F}_{2^m}$ is the unique solution to the equation $a + x \equiv 0$ in $\mathbb{F}_{2^m}$.

- Multiplicative inverse: If $a \in \mathbb{F}_{2^m}$, $a \neq 0$, then the multiplicative inverse a^{-1} of a in $\mathbb{F}_{2^m}$ is the unique solution to the equation $ax \equiv 1$ in $\mathbb{F}_{2^m}$.

In order to increase efficiency and interoperability, the characteristic binary finite fields used should have:

$$m \in \{163, 233, 239, 283, 409, 571\}$$

These fields were chosen in order to construct a suitable Koblitz curve whose order is 2 or 4 times a prime over $\mathbb{F}_{2^m}$. The field with $m = 239$ is an anomaly shown here because it has already been widely used in practice. The field with $m = 283$ is an anomaly that is often included to align with the U.S. government's recommended elliptic curve domain parameters.

Addition and multiplication should be performed using one of the irreducible binary polynomials of degree m in Figure 3.2.1.2.A below. These polynomials enable efficient calculation of field operations, except for the polynomial with $m = 239$ which is an anomaly shown here because it has been widely deployed.

Field	Reduction Polynomial(s)
$\mathbb{F}_{2^{163}}$	$f(x) = x^{163}+x^7+x^6+x^3+1$
$\mathbb{F}_{2^{233}}$	$f(x) = x^{233}+x^{74}+1$
$\mathbb{F}_{2^{239}}$	$f(x) = x^{239}+x^{36}+1$ or $x^{239}+x^{158}+1$
$\mathbb{F}_{2^{283}}$	$f(x) = x^{283}+x^{12}+x^7+x^5+1$
$\mathbb{F}_{2^{409}}$	$f(x) = x^{409}+x^{87}+1$
$\mathbb{F}_{2^{571}}$	$f(x) = x^{571}+x^{10}+x^5+x^2+1$

Figure 3.2.1.2.A Binary Finite Field Reduction Polynomials

3.2.2 Elliptic Curves

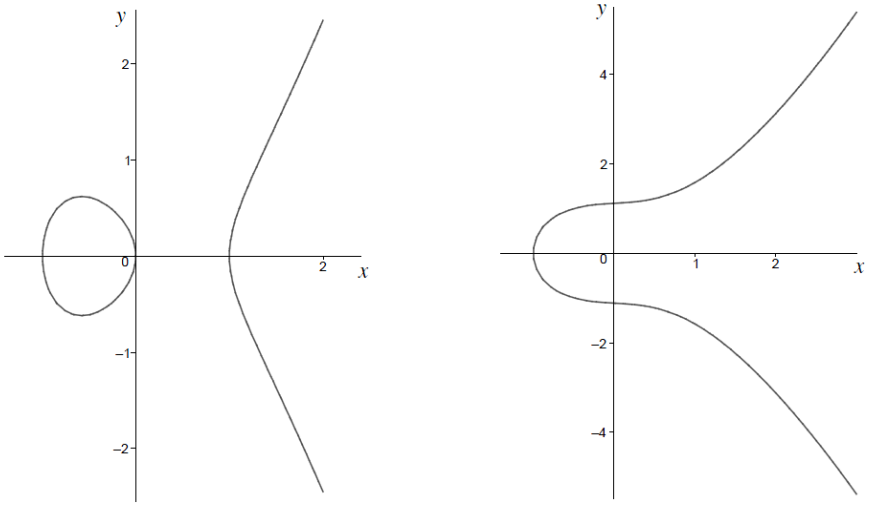
Elliptic curves are most commonly shown in the form of the simplified Weierstrass equation in the form of:

$$y^2 = x^3 + ax + b$$

where

$$4a^3 + 27b^2 \neq 0$$

This condition is critical to ensure that the elliptic curve is "smooth", i.e. that there are no points at which the curve has two or more distinct tangent lines. The curves shown in Figure 3.2.2.A illustrate examples of elliptic curves satisfying this condition.



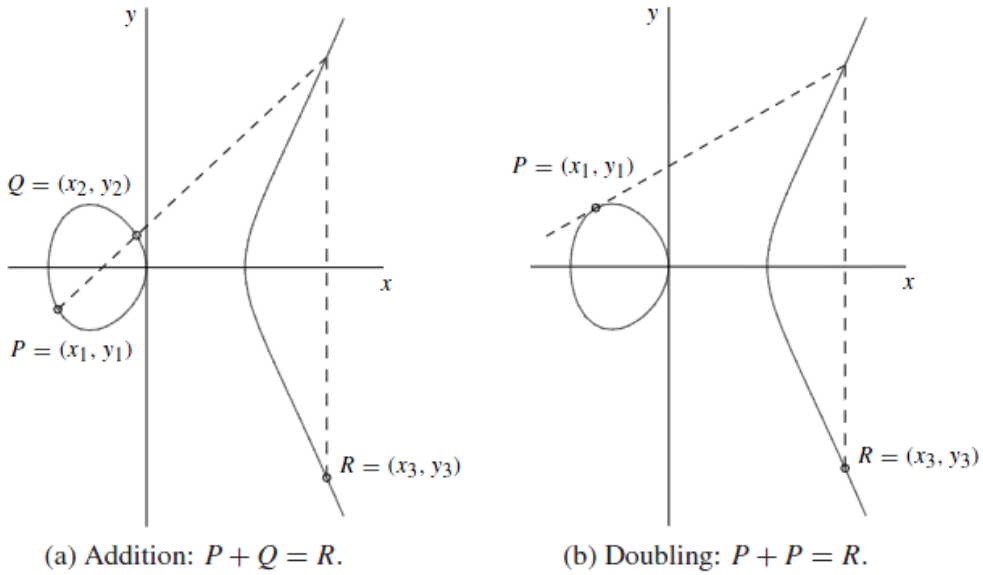
(a) $E_1 : y^2 = x^3 - x$ (b) $E_2 : y^2 = x^3 + \frac{1}{4}x + \frac{5}{4}$

Figure 3.2.2.A Sample Elliptic Curves [10]

The security of ECC is based on the elliptic curve discrete logarithm problem (ECDLP), which arises when elliptic curves are used over finite fields. The ECDLP is [10]: given an elliptic curve E defined over a finite field $\mathbb{F}_q$, a point $P \in E(\mathbb{F}_q)$ or order n, and a point

$Q \epsilon <P>$, find the integer $l \epsilon [0, n-1]$ such that $Q = lP$. The integer l is called the discrete logarithm of Q to the base P, denoted $l = log_P Q$. The elliptic curve domain parameters for cryptographic schemes should be carefully chosen in order to resist all known attacks on the ECDLP. However, since the methods for computing solutions to the ECDLP are much less efficient then methods used for computing solutions to integer factorization (used in RSA) ECC can provide the same level of security as RSA with smaller key lengths, and scales much better at higher levels of security than RSA.

When an elliptic curve E is defined over a field (call it K) there exist rules for adding two points in $E(K)$ to give a third point in $E(K)$. This operation is commonly known as point addition. Furthermore, there also exist rules for doubling a point as to obtain a third point, an operation commonly known as point doubling. Figure 3.2.2.B below shows a geometric representation of both of these rules.



(a) Addition: $P + Q = R$. (b) Doubling: $P + P = R$.

Figure 3.2.2.B Geometric Representation of Point Addition and Point Doubling [10]

Algebraic formulas for these operations can be derived from the geometric representation. The exact formulas themselves (the group law) will vary depending on whether you are using a simplified Weierstrass form or the complete form. They will also vary depending on the characteristic q of the underlying field [10]:

- The characteristic of the underlying field K is not 2 or 3 (e.g. $K = \mathbb{F}_p$ where $p > 3$ is a prime)
- The curve E is non-supersingular of the form over $K = \mathbb{F}_{2^m}$
- The curve E is supersingular of the form over $K = \mathbb{F}_{2^m}$

The easiest group law to understand is for that of the simplified Weierstrass form for *char(K)≠2,3*, shown in Figure 3.2.2.C. Group laws for the simplified Weierstrass form for *char(K)=2* are shown in Figures 3.2.2.D and 3.2.2.E for non-supersingular and supersingular curves respectively.

1. *Identity*. $P + \infty = \infty + P = P$ for all $P \in E(K)$.
2. *Negatives*. If $P = (x, y) \in E(K)$, then $(x, y) + (x, -y) = \infty$. The point $(x, -y)$ is denoted by $-P$ and is called the *negative* of P; note that $-P$ is indeed a point in $E(K)$. Also, $-\infty = \infty$.
3. *Point addition*. Let $P = (x_1, y_1) \in E(K)$ and $Q = (x_2, y_2) \in E(K)$, where $P \neq \pm Q$. Then $P + Q = (x_3, y_3)$, where

$$x_3 = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)^2 - x_1 - x_2 \quad \text{and} \quad y_3 = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x_1 - x_3) - y_1.$$

4. *Point doubling*. Let $P = (x_1, y_1) \in E(K)$, where $P \neq -P$. Then $2P = (x_3, y_3)$, where

$$x_3 = \left(\frac{3x_1^2 + a}{2y_1}\right)^2 - 2x_1 \quad \text{and} \quad y_3 = \left(\frac{3x_1^2 + a}{2y_1}\right)(x_1 - x_3) - y_1.$$

Figure 3.2.2.C Group Law for $E(\mathbb{F}_p)$: $y^2=x^3+ax+b$, $char(K) \neq 2,3$ [10]

1. *Identity*. $P+\infty=\infty+P=P$ for all $P \in E(\mathbb{F}_{2^m})$.
2. *Negatives*. If $P=(x, y) \in E(\mathbb{F}_{2^m})$, then $(x, y)+(x, x+y)=\infty$. The point $(x, x+y)$ is denoted by $-P$ and is called the *negative* of P; note that $-P$ is indeed a point in $E(\mathbb{F}_{2^m})$. Also, $-\infty=\infty$.
3. *Point addition*. Let $P=(x_1, y_1) \in E(\mathbb{F}_{2^m})$ and $Q=(x_2, y_2) \in E(\mathbb{F}_{2^m})$, where $P \neq \pm Q$. Then $P+Q=(x_3, y_3)$, where

$$x_3=\lambda^2+\lambda+x_1+x_2+a \quad \text{and} \quad y_3=\lambda(x_1+x_3)+x_3+y_1$$

with $\lambda=(y_1+y_2)/(x_1+x_2)$.

4. *Point doubling*. Let $P=(x_1, y_1) \in E(\mathbb{F}_{2^m})$, where $P \neq -P$. Then $2P=(x_3, y_3)$, where

$$x_3=\lambda^2+\lambda+a=x_1^2+\frac{b}{x_1^2} \quad \text{and} \quad y_3=x_1^2+\lambda x_3+x_3$$

with $\lambda=x_1+y_1/x_1$.

Figure 3.2.2.D Group Law for non-supersingular $E(\mathbb{F}_{2^m})$: $y^2+xy=x^3+ax^2+b$ [10]

1. *Identity*. $P+\infty=\infty+P=P$ for all $P \in E(\mathbb{F}_{2^m})$.
2. *Negatives*. If $P=(x, y) \in E(\mathbb{F}_{2^m})$, then $(x, y)+(x, y+c)=\infty$. The point $(x, y+c)$ is denoted by $-P$ and is called the *negative* of P; note that $-P$ is indeed a point in $E(\mathbb{F}_{2^m})$. Also, $-\infty=\infty$.
3. *Point addition*. Let $P=(x_1, y_1) \in E(\mathbb{F}_{2^m})$ and $Q=(x_2, y_2) \in E(\mathbb{F}_{2^m})$, where $P \neq \pm Q$. Then $P+Q=(x_3, y_3)$, where

$$x_3=\left(\frac{y_1+y_2}{x_1+x_2}\right)^2+x_1+x_2 \quad \text{and} \quad y_3=\left(\frac{y_1+y_2}{x_1+x_2}\right)(x_1+x_3)+y_1+c.$$

4. *Point doubling*. Let $P=(x_1, y_1) \in E(\mathbb{F}_{2^m})$, where $P \neq -P$. Then $2P=(x_3, y_3)$, where

$$x_3=\left(\frac{x_1^2+a}{c}\right)^2 \quad \text{and} \quad y_3=\left(\frac{x_1^2+a}{c}\right)(x_1+x_3)+y_1+c.$$

Figure 3.2.2.E Group Law for supersingular $E(\mathbb{F}_{2^m})$: $y^2+cy=x^3+ax+b$ [10]

3.2.3 Projective Coordinates

The group laws shown in section 3.2.2 illustrate that the formulas for point addition and point doubling require field inversions and field multiplications. These are complex operations for the very large fields typically used in cryptographic applications. If inversion in a field K is significantly more expensive than multiplication (and it typically has a cost of roughly 80 field multiplications [10]), then the use of a technique known as projective coordinates may be advantageous to use.

Projective coordinates essentially works by defining an equivalence relationship between a field K and a set $K^3 \setminus \{0,0,0\}$. The relationship is obtained by replacing x with X/Z^c and y with Y/Z^d, and clearing the denominators. We end up with a 1-1 relationship between the affine points that lie on E and the projective points on E. There are a number of different versions of projective coordinates, with varying values of c and d.

In the "standard projective coordinates" c and d are both set to one. Another form of projective coordinates known as "Jacobian coordinates" sets $c=2$ and $d=3$. This changes the simplified Weierstrass equation from:

$$y^2 = x^3 + ax + b$$

to the projective form:

$$Y^2 = X^3 + aXZ^4 + bZ^6$$

The result of this change allows a new group law to be formed in which point doubling can be computed using six field squarings and four field multiplications [10]. The use of field inversions is now no longer required. Algorithms also exist to perform point multiplication between points in different coordinate systems, such as affine and

Jacobian. Jacobian coordinates yield the fastest point doubling, while mixed Jacobian-affine coordinates yield the fastest point addition.

A third type of coordinate system is "Chudnovsky coordinates". In Chudnovsky coordinates Jacobian coordinates *(X:Y:Z)* are represented as $(X:Y:Z:Z^2:Z^3)$. There are some point multiplication algorithms that make use of the redundancy in Chudnovsky coordinates and use mixed Jacobian-Chudnovsky and mixed Chudnovsky-affine coordinates for point addition. Figure 3.2.3.A below gives some example operation counts for using projective coordinates in point addition. In the figure *A* represents affine coordinates, *P* represents standard projective coordinates, *J* represents Jacobian coordinates, and *C* represents Chudnovsky coordinates. The mathematical operations of field inversion, field multiplication, and field squaring are representated as *I*, *M*, and *S* respectively.

Doubling		General addition		Mixed coordinates	
$2A \to A$	$1I, 2M, 2S$	$A + A \to A$	$1I, 2M, 1S$	$J + A \to J$	$8M, 3S$
$2P \to P$	$7M, 3S$	$P + P \to P$	$12M, 2S$	$J + C \to J$	$11M, 3S$
$2J \to J$	$4M, 4S$	$J + J \to J$	$12M, 4S$	$C + A \to C$	$8M, 3S$
$2C \to C$	$5M, 4S$	$C + C \to C$	$11M, 3S$		

Figure 3.2.3.A Operation Counts on $y^2 = x^3 - 3x+b$ [10]

3.2.4 Point Multiplication

In cryptographic applications point multiplication (the computation of *kP* where *P* is a point on the curve and *k* is an integer) dominates the execution time of ECC schemes. There are three cases where point multiplication occurs:

- *kP* where precomputation must be online
- *kP* for *P* known in advance and precomputation may be offline

- $kP + lQ$ where only the precomputation for P may be done offline

The last two cases are motivated by the Elliptic Curve Digital Signature Algorithm (ECDSA), where signature generation requires a calculation kP where P is fixed, and signature verification requires a calculation $kP + lQ$ where P is fixed and Q is known a priori.

There are a number of mathematical techniques that can be used in order to increase the efficiency of point multiplications. Some methods, such the "sliding-window methods", require that extra memory be available. Additionally, if the point P is fixed and some storage is available, then the point multiplication kP can be accelerated by pre-computing some of the data dependent on P using a type of fixed-base windowing method such as that proposed by Brickell, Gordon, McCurley, and Wilson [10]. Shamir's Trick is yet another method used specifically to speed up the calculation of $kP + lQ$ by performing simultaneous multiple point multiplication [10].

3.3 Domain Parameters

As stated previously, the elliptic curve domain parameters for cryptographic schemes should be carefully chosen in order to resist all known attacks on the ECDLP. In general, for elliptic curves over a finite field $\mathbb{F}_{q^m}$, the following domain parameters are required to be specified:

$$D = (q, FR, S, a, b, P, n, h)$$

Where:

q – field order

FR – field representation

S – seed, used if the elliptic curve was generated randomly

a & b – coefficients in the field $\mathbb{F}_{q^m}$ that define the equation over the field

P – the base point $P=(x_p, y_p) \epsilon \mathbb{F}_{q^m}$ that has prime order

n – *the order of* P

h – *the cofactor* $h=\#E(\mathbb{F}_{q^m}) / n$

This section describes the domain parameters needed to generate curves for the prime and binary finite fields used in ECC. We then go on to discuss the use of standardized special curves and the generation of new random curves, discussing the pros and cons of each.

3.3.1 Prime Field Elliptic Curves

For elliptic curve domain parameters over $\mathbb{F}_p$ the domain parameters are the sextuple:

$$D = (p, a, b, P, n, h)$$

They consist of an integer p specifying the finite field along with certain general domain parameters defined above. Elliptic curve domain parameters over $\mathbb{F}_p$ precisely specify an elliptic curve and a base point. This is necessary to define public-key cryptography schemes based on ECC [24]. If the elliptic curve domain parameters are verifiably random than they should be accompanied by the seed value S from which they are derived [24].

3.3.2 Binary Field Elliptic Curves

For elliptic curve domain parameters over $\mathbb{F}_{2^m}$ the domain parameters are the septuple:

$$D = (m, f(x), a, b, P, n, h)$$

They consist of an integer *m* specifying the finite field $\mathbb{F}_{2^m}$, an irreducible binary polynomial *f(x)* of degree *m* specifying the representation of $\mathbb{F}_{2^m}$, along with certain general domain parameters defined above. Elliptic curve domain parameters over $\mathbb{F}_{2^m}$ precisely specify an elliptic curve and a base point. This is necessary to define public-key cryptography schemes based on ECC [24]. If the elliptic curve domain parameters are verifiably random than they should be accompanied by the seed value *S* from which they are derived [24].

3.3.3 Standardized Versus Random Curves

In order to increase efficiency of cryptographic implementations and to prevent all known attacks, various standardized domain parameters have been developed for elliptic curves over both prime and finite fields. These standardized, or "special", curves have been published by the SECG [24] and are recommended by NIST for use in U.S. government applications. However, in order to guard against future attacks against these curves one might decide to generate a new curve randomly but that has a validation process that proves the new curve resists all known attacks on the ECDLP. Fortunately algorithms exist to accomplish this very task [10].

The conventional wisdom of ECC has been, as described by Koblitz [27]:

- For greatest security choose parameters as randomly as possible
- It is safest to choose the defining equation to have random coefficients
- It is okay to use special curves for reasons of efficiency if you insist, however that choice may one day come back to bit you

Recent work on isogenies in elliptic curve cryptography has shown that there are various scenarios in which a special curve is better than a random curve. Isogenies, simply put, allow one to transport the discrete logarithm problem from one curve to another. It is "random self-reducible" within a set of endomorphism classes with small conductor gaps. Work in this area has shown that we need to assume that some version of a Weil Descent attack or another approach someday will lead to a faster-than-sqrt attack on a small but non-negligible portion of random curves [27].

It is unknown at this time whether random curves are truly more secure than special curves. Therefore, for control systems for the Smart Grid and NGIPS following the NIST recommendation seems to be the most prudent.

3.4 Known Attack Mechanisms against ECC

This section presents a basic overview of the theory behind various attacks against ECC, focusing more on the implications of these attack methods and the countermeasures to these attacks. Attacks against ECC focus on finding ways to solve the ECDLP in sub-exponential time. It should be noted that using ECC technologies such as the Elliptic Curve Digital Signature Algorithm (ECDSA) using any of the SECG recommended elliptic curve domain parameters [24] will provide protection against all known attacks (i.e. render these attacks computationally infeasible).

3.4.1 Naïve Method

The most naïve method for solving the ECDLP is to perform an exhaustive search where one computes the sequence of points *1P, 2P, 3P,…lP* until *Q* is encountered. On average

this will take *n/2* steps. Therefore the naïve method can be circumvented by selecting elliptic curve domain parameters with *n* being sufficiently large to represent an infeasible number of calculations (e.g. $n = 2^{80}$) [10]. Therefore other methods of solving the ECDLP must be sought.

The best general-purpose attack known on the ECDLP is the combination of the Pohlig-Hellman algorithm and Pollard's rho algorithm. Even these attacks can have an exponential running time depending on the selection of the domain parameters. However, it should be noted that there exists no mathematical proof that there does not exist an efficient algorithm for solving the ECDLP. Some evidence for the intractability of the ECDLP does exist and researchers have been studying the problem extensively since 1985 when it was first proposed [10].

3.4.2 Pholig-Hellman Attack

The Pholig-Hellman attack uses an algorithm that reduces the computation of $l = log_p Q$ to the computation of discrete logarithms in the prime order subgroups of $<P>$. Therefore in order to maximize resistance to the attack domain parameters should be selected such that the order *n* of *P* is divisible by a large prime so that the subgroup field is large.

3.4.3 Pollard's rho Attack

The idea of Pollard's rho attack is to find distinct pairs *(c', d')* and *(c'', d'')* of integers modulo *n* such that:

$$c'P + d'Q = c''P + d''Q$$

Hence $l = log_p Q$ can be obtained by computing

$$L = (c'-c'')(d'-d'')^{-1} \bmod n$$

This attack on its own takes roughly the same expected time as the naïve method but has negligible storage requirements [10]. There are multiple ways of speeding up this attack, including methods of parallelizing the attack to allow multiple processors to work together to solve an ECDLP instance in which the speedup is linear to the number of processors used. The processors also do not have to communicate to each other and need only limited communications to a central server.

3.4.4 Index-Calculus Attacks

Index-calculus algorithms are the most powerful methods known for computing discrete logarithms in groups such as the multiplicative group of a finite field. The question that naturally arises is if these algorithms can be used to solve the ECDLP in sub-exponential time. The problem for the ECDLP is that no one knows how to efficiently lift points in $E(\mathbb{F}_p)$ to $E(\mathbb{Q})$ and it has been proven under some reasonable assumptions that the number of points of the small height required for these algorithms is extremely small so that only an insignificant proportion of the points can be lifted. Therefore, so far no one has found an index-calculus approach that yields a general subexponential-time (or better) algorithm for the ECDLP [10].

3.4.5 Isomorphism Attacks

Isomorphism attacks essentially try to reduce the ECDLP to the DLP in groups for which subexponential-time (or faster) algorithms are known. Consequently the ECDLP for

curves on which an isomorphism attack are found can be efficiently solved. Weil and Tate pairing attacks and Weil descent attacks are examples of isomorphism attacks.

3.5 Cryptographic Protocols Useful for Control Systems

As discussed in section 1.3.1 the primary need for control systems is to verify data integrity and authentication. This need is fulfilled in corporate / non-control systems through the use of the Digital Signature Algorithm discussed in section 2.3.2.2. However, as discussed in section 2.3.2.3 the use of this algorithm is infeasible for control systems. Elliptic curves offer us an alternative path through the use of the Elliptic Curve Digital Signature Algorithm (ECDSA). There are also a number of other alternative elliptic curve signature schemes, such as Elliptic Curve ElGamal Signatures (ECES) and Abbreviated ECES Signatures (AECES). Since ECDSA is approved by NIST and included in their NSA Suite B it is therefore the most suitable candidate for use in control systems. The subsections below detail the algorithm, beginning with generating private and public keys for use in ECDSA.

3.5.1 Key Generation

ECC key pairs are associated with the particular elliptic curve domain parameters used in the generation of the key pair. The public key is a randomly selected point Q in the group $<P>$ generated by P. The private key that corresponds to the public key is the solution to the ECDLP $d = log_p Q$. The entity that is generating the key pair must have the assurance that the domain parameters are valid (i.e. resistant to all known attacks),

and the association between the domain parameters and the public key must be verifiable by all entities in the communication.

In non-control / corporate systems this would normally be done by a certification authority that generates a certificate attesting to the association between a public key and its domain parameters. Large scale control systems such as the Smart Grid will need to perform the same function on some level. For smaller control systems, such as those planned for use on US Navy ships for NGIPS, this association can be achieved by context (i.e. all entities in the system use the same domain parameters).

Algorithm 3.5.1.A below illustrates how to generate an ECC key pair assuming valid domain parameters. It is critical that the number d generated be random, as in the likelihood that any particular value of d would be chosen over any other value is so small that an adversary is unable to narrow down the search space for d. This is akin to the idea that someone should not select a password that includes their spouse's name.

Algorithm 3.5.1.A [10] – Generating ECC Key Pair

INPUT: Domain Parameters $D = (q, FR, S, a, b, G, n, h)$

OUTPUT: Public key Q, Private key d

1. Randomly select $d \epsilon_R [1, n-1]$
2. Compute $Q = dP$
3. Return (Q, d)

Entities that receive a public key Q and a set of associated domain parameters will need to validate the public key to ensure that the private key actually exists and that the keys

lie on the curve. Failure to perform public key validation could allow an attacker to try to get you to use the invalid public key in such a way that information about your private key could be revealed. Algorithm 3.5.1.B illustrates how to perform the required validation.

Algorithm 3.5.1.B [10] – ECC Public Key Validation

INPUT: Domain Parameters $D = (q, FR, S, a, b, G, n, h)$, public key Q

OUTPUT: Acceptance or rejection of the validity of Q

1. Verify that $Q \neq \infty$
2. Verify that x_Q and y_Q are properly represented elements of $\mathbb{F}_q$ (i.e. integers in the interval $[0, q-1]$ if the field is prime, and bit strings of length m bits if the field is a binary field of order 2^m)
3. Verify that Q satisfies the elliptic curve equation defined by a and b
4. Verify that $nQ = \infty$
5. If any verification fails then return invalid, else return valid

Note that the check is step 4 of Algorithm 3.5.1.B involves an expensive point multiplication. Faster methods do exist for certain curves. For example, if the cofactor h of a prime field curve is equal to 1 (which is usually the case in practice and for all of the SECG recommend prime field curves [24]) then successful completion of the checks in steps 1 through 3 imply that $nQ = \infty$ [10].

3.5.2 Elliptic Curve Digital Signature Algorithm (ECDSA)

Algorithms 3.5.2A and 3.5.2.B below define how to generate and verify ECDSA signatures, respectively. In these algorithms, *H* denotes some cryptographic hash function whose outputs have bitlength no more than that of *n*. If this condition is not satisfied though, the outputs of *H* can be truncated. More information on hash functions can be found in section 3.5.3 below.

ECDSA uses a per-message secret *k* that if discovered by an adversary can be used to recover the private key since:

$$d = r^{-1}(ks-e) \bmod n \qquad \text{where } e = H(m)$$

Furthermore it has been shown that if an adversary even obtains a few consecutive bits of the secret *k* then the adversary can easily compute the private key. It is therefore of utmost importance that *k* be randomly and securely generated, securely stored, and securely destroyed after it has been used. The reason why *k* should be generated randomly is to help ensure that *k* does not repeat. If the same per-message secret *k* was used to generate ECDSA signatures *(r, s1)* and *(r, s2)* on two messages *m1* and *m2* then if $s1 \neq s2$ (which with overwhelming probability they will not be equal) it can be shown that:

$$k \equiv (s_1-s_2)^{-1}(e_1-e_2) \bmod n \quad \text{where } e_1 = H(m_1) \text{ and } e_2 = H(m_2) \text{ [10]}$$

Thus an adversary could determine *k* and then use it to determine the private key *d*.

Algorithm 3.5.2.A [10] – ECDSA Signature Generation

INPUT: Domain Parameters $D = (q, FR, S, a, b, P, n, h)$, private key d, message m

OUTPUT: Signature (r, s)

1. Randomly select $k \epsilon_R [1, n-1]$
2. Compute $kP = (x_1, y_1)$ and convert x_1 to an integer $\overline{x_1}$
3. Compute $r = \overline{x_1} \bmod n$ and if $r = 0$ go to step 1
4. Compute $e = H(m)$
5. Compute $s = k^{-1}(e + dr) \bmod n$ and if $s = 0$ go to step 1
6. Return (r, s)

Algorithm 3.5.2.B [10] – ECDSA Signature Verification

INPUT: Domain Parameters $D = (q, FR, S, a, b, P, n, h)$, public key Q, message m, signature (r, s)

OUTPUT: Acceptance or rejection of the signature

1. Verify that r and s are integers in the interval $[1, n-1]$, if any verification fails then reject the signature
2. Compute $e = H(m)$
3. Compute $w = s^{-1} \bmod n$
4. Compute $u_1 = ew \bmod n$ and $u_2 = rw \bmod n$
5. Compute $X = u_1P + u_2Q$
6. If $X = \infty$ then reject the signature
7. Convert the x-coordinate x_1 of X to an integer $\overline{x_1}$; compute $v = \overline{x_1} \bmod n$

8. If $v = r$ then accept the signature, else reject

3.5.3 Supported Secure Hash Algorithms

Cryptographic hash functions are used in many applications within ECC, including verifiably random curve and base point generators, key derivation functions, and ECDSA. According to the SECG [24] supported hash functions for ECC are:

- SHA-1
- SHA-224
- SHA-256
- SHA-384
- SHA-512

NIST is holding a competition for a new SHA-3 hash function that is scheduled for completion this year (2012) [28]. Future versions of SECG standards are likely to allow use of the new SHA-3 [23].

The security level associated with a hash function depends on its application. Collision resistance is generally needed for computing message digests in ECDSA, and where collision resistance is needed the security level is at most half the output length (in bits) of the hash function. Recent results have shown that SHA-1 provides less than 80 bits of collision resistance [23] and therefore should be used with ECDSA only when providing backwards compatibility.

3.6 Comparing RSA Signatures to ECDSA

It has already been stated that ECDSA offers security equivalent to RSA using much smaller key sizes which can lead to increased efficiency. Figure 3.6.A below shows a chart of comparable key sizes for equivalent levels of security. Figures 3.6.B through 3.6.D below show execution times for ECDSA and RSA signature algorithms running algorithms for key generation, signature generation, and signature verification.

These times were taken from tests performed on an Intel Pentium 4 2.0 GHz machine with 512MB of RAM, on a 100KB text file used as a message [29]. As discussed previously though, the architecture for control system components such as PLCs is radically different than that of an x86 architecture, and therefore these timings only provide a very basic indication of what the performance of ECC might look like in control system applications. Further research is required in this area.

Symmetric	ECC	RSA
80	163	1024
112	233	2240
128	283	3072
192	409	7680
256	571	15360

Figure 3.6.A ECC vs RSA Comparable Key Sizes (in bits) [29]

Key Length		Time (s)	
ECC	RSA	ECC	RSA
163	1024	0.08	0.16
233	2240	0.18	7.47
283	3072	0.27	9.80
409	7680	0.64	133.90
571	15360	1.44	679.06

Figure 3.6.B ECC vs RSA Key Generation [29]

Key Length		Time (s)	
ECC	RSA	ECC	RSA
163	1024	0.15	0.01
233	2240	0.34	0.15
283	3072	0.59	0.21
409	7680	1.18	1.53
571	15360	3.07	9.20

Figure 3.6.C ECC vs RSA Signature Generation [29]

Key Length		Time (s)	
ECC	RSA	ECC	RSA
163	1024	0.23	0.01
233	2240	0.51	0.01
283	3072	0.86	0.01
409	7680	1.80	0.01
571	15360	4.53	0.03

Figure 3.6.D ECC vs RSA Signature Verification [29]

The results show that ECC outperforms RSA significantly in key generation, and performs signature generation faster than RSA for higher key sizes. RSA outperforms ECC in signature verification significantly for all key sizes. The times appear to show that RSA signature verification time is fairly independent of key size and for practical

purposes this is true, however this is really just do to the resolution at which testing was performed (for example RSA signature verification at 7680 bit key size should be approximately 0.008 seconds while signature verification at 15360 bit key size should be approximately 0.032 seconds). ECC signature verification grows linearly with an increase in key size, however the times show that RSA significantly outperforms ECC in this area. Signature verification is therefore of particular concern in looking at implementing ECC signature algorithms for control systems. At stronger levels of security with larger key sizes, ECDSA will outperform RSA for the total message transmission (including both signature generation and verification) since ECC signature verification timing scales linearly while RSA signature generation timing scales exponentially (due to the exponential increase in key sizes) for equivalent levels of security.

A variant of ECDSA, known as the Elliptic Curve Korean Certificate-based Digital Signature Algorithm (EC-KCDSA) may hold promise if ECDSA does not proof to be efficient for use in control systems. In EC-KCDSA the signer's private key is an integer d ϵ_R *[1, n-1]* as is in ECDSA, but the public key is instead $Q = d^{-1}P$ (instead of dP). This allows for the design of signature generation and verification procedures that do not require performing modular inversion and therefore could potentially be more applicable in meeting control system needs should ECDSA prove impractical. EC-KCDSA has been proven secure under the assumptions that the discrete logarithm problem is intractable and that the hash function is a random function.

An alternative variant of ECDSA, proposed by Antipa et al (2005) [32], involves reconstructing the ephermeral elliptic curve point R from the signature component r. In other words one converts the ECDSA signature (r, s) over some message m to a new

ECDSA* signature *(R, s)*. Antipa et al provide a general procedure for this change which accepts the ECDSA signature as an input, performs the reconstruction/conversion, and returns either acceptance or rejection of the signature. This speeds up ECDSA signature verification by 35-40% at the cost of only a small number of bits appended to traditional ECDSA signatures.

Unfortunately, the EC-KCDSA algorithm and the ECDSA*algorithms are non-compliant with any of the existing ECDSA standards.

3.7 OpenSSL ECC Implementation

As much as has been discussed up to this point on the underlying mathematics and implementation theory of ECC and ECDSA in particular most engineers will never develop their own implementations. They will instead rely on existing implementations which they will incorporate into their own products. OpenSSL provides a suite of cryptographic toolkits including toolkits for ECC written in C+ that can be readily incorporated into new products.

The ECC implementations present in OpenSSL were contributed by Sun (now Oracle) and offered freely with "patent peace provision" language (meaning they will not sue anyone for using their implementation and ask, but not require, that you do not sue them if they use a product you develop with their technology). This implementation was theoretically written in a way that avoids any patented method by basing the implementation on the current IETF [26] draft [30]. However the issue of patents appears to be far from settled, and some versions of Linux such as Red Hat do not include

the ECC toolkits in their versions of OpenSSL. There also exist JAVA and .NET implementations.

While it is true that in control systems the OpenSSL toolkit cannot be used by PLCs (since they cannot run C+ binaries), VME technologies including SoftPLC may be able to leverage the OpenSSL implementation. Currently there are no known implementations of ECC written specifically for control systems that are compliant with IEC 61131-3 or IEC 61499.

3.8 ECC Certificates

As discussed in section 3.5.1, certificates play a key role in cryptographic systems. In ECC, they are used in order to associate a public key with a set of domain parameters. The problem with ECC is that current there are no Certificate Authorities supported by major web browsers for ECC, causing some to not consider ECC a true public-key cryptography scheme. SECG is working hard on changing this, establishing itself as an ECC certificate authority and publishing standards to indicate ECC keys and their usage within X.509 certificates [31]. However there is still significant work to do in this area in order to truly make ECC a viable solution for complex control systems such as that in the Smart Grid. For smaller control systems such as those planned for usage in NGIPS the lack of a strong ECC certificate authority is not as much of a roadblock.

CHAPTER 4: PROPOSAL FOR PROJECT

ECDSA shows promise for use in control systems, however there are a number of questions that arise from the perspective of a controls engineer such as:

- How difficult will this be to implement?
- What impacts will this have on the performance of my controls algorithms?
- What kind of software maintenance is needed to support ECDSA in control systems?
- What are the costs of implementing these algorithms?

In order to begin to answer these questions, a prototype control system must be developed that matches architectures used in real applications to run actual control algorithms. The goal of the prototype will be to determine the viability of using ECDSA in control system data authentication and verification.

Given the sheer complexity of developing a brand new implementation of ECDSA in IEC 61131-3 code "proof of concept" studies are needed to more accurately assess the validity of using ECC technology in control systems before significant time and money are invested. We propose a project to perform this "proof of concept" testing in which two SoftPLCs running on VME racks will be configured that utilize the existing implementations of ECDSA in OpenSSL. Successful "proof of concept" testing will, in future projects, be followed up by developing an efficient implementation of IEC 61131-3 code that can be utilized for regular PLCs, opening the door to the widespread industrial and military adoption of ECC and specifically ECDSA in control systems.

The SoftPLCs and VMEs will be configured to match the existing control system architecture used on some classes of US Navy ships that are already outfitted with an integrated power system. Siemens WinAC software will be used to run the SoftPLCs, and sample control algorithms will be developed in IEC 61131-3 compliant code that will perform simulated functions similar to those that will be required in an NGIPS or Smart Grid controls system. Siemens WinAC allows a SoftPLC developer to create IEC 61131-3 code that is capable of calling C+ and JAVA code running on an x86 platform such as Windows XP. This will enable the utilization of OpenSSL for ECDSA algorithms in the control system allowing us to perform a series of timing and cryptographic validation tests. The goal of these tests will be to determine what the impacts will be on the control system when ECDSA is utilized.

The project will allow the development of a software template that can be easily reused by control system engineers in other applications at minimal cost. Currently, PLC instructions such as "MSG" (for message) are used IEC 61131-3 code and with only minor adjustments communications messages can be programmed between PLCs. This project will endeavor to create a similar kind of application instruction. The project will also include additional features beyond messaging such as enhanced alarming functions that will not only indicate communications status but failures in signature verifications indicating a potential hardware failure or adversary attack.

A simple HMI application will be developed along with the two SoftPLCs that will communicate to both and accept simulated inputs from an operator as would be done in a normal control system. Scripting will be developed in the application to enable the use of

ECDSA between the HMI and the SoftPLCs, including the annunciation and acknowledgement of alarms related to signature verifications.

Prime field ECC will be utilized in the project. Testing will be performed on each of the five recommended SECG curves in order to establish a relationship between control system performance and key size.

REFERENCES

1. Bouhafs, F., Mackay, M., Merabti, M. (2012). “Links to the Future.” IEEE Power and Energy Magazine 1540-7977/12, pp. 24-32
2. Yan, Y., Qian, Y., Sharif, H., Tipper, D. (2012) “A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements, and Challenges.” IEEE Communications Surveys & Tutorials, Accepted for Publication 1553-877X/12
3. Yan, Y., Qian, Y., Sharif, H., Tipper, D. (2012) “A Survey on Cyber Security for Smart Grid Communications.” IEEE Communications Surveys & Tutorials, Accepted for Publication 1553-877X/12
4. Liu, Y., Ning, P., Reiter, M. (2009) “False data injection attacks against state estimation in electric power grids.” In Proc. ACM Conference on Computer and Communications Security (CCS 09)
5. Baumeister, T. (2011) “Adapting PKI for the Smart Grid.” IEEE SmartGridComm, 978-1-4577-1702-4/11
6. NISTIR 7628 Volume 1 (2010) “Guidelines for Smart Grid Cyber Security: Vol. 1, Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements.”
7. Naval Sea Systems Command (2007) “Next Generation Integrated Power System Technology Development Roadmap.” Ser 05D/349 of 30 Nov 2007

8. Doerry, N., CAPT USN, "Next Generation Integrated Power Systems for the Future Fleet," Presented at the Corbin A. McNeill Symposium, United States Naval Academy, Annapolis, MD, March 30, 2009
9. Doerry, N., Scherer, T., Cohen, J., Guertin, N., "Open Architecture Machinery Control System ," Presented at ASNE Intelligent Ships Symposium 2011, May 25-26, 2011, Philadelphia, PA.

   Also Published in ASNE Naval Engineers Journal, Mar 2012, Vol 124 No. 1, pp. 101-114.
10. Hankerson, D., Menezes, A., Vanstone, S. (2004) Guide to Elliptic Curve Cryptography, ©2004, Springer-Verlag New York, Inc.
11. Wikipedia: RSA Algorithm (http://en.wikipedia.org/wiki/RSA_%28algorithm%29) Accessed: 3rd July, 2012
12. Wikipedia: Digital Signature Algorithm (http://en.wikipedia.org/wiki/Digital_Signature_Algorithm) Accessed: 3rd July, 2012
13. Wikipedia: Key Size (http://en.wikipedia.org/wiki/Key_size) Accessed: 3rd July 2012
14. Miller, V.S. (1985). “Use of elliptic curves in cryptography.” Advances in Cryptology Proc. Crypto ’85, LNCS 218, H.C. Williams, Ed., Springer-Verlag, pp. 417-426
15. Koblitz, N. (1987). “Elliptic curve cryptosystems.” Mathematics of Computation, Vol. 48, No. 177, p. 279-287

16. ANSI X9.62 (1999). "Public Key Cryptography for the Financial Services Industry: The Elliptic Curve Digital Signature Algorithm (ECDSA)
17. ANSI X9.63 (2000- Working Draft). "Public Key Cryptography for the Financial Services Industry: Elliptic Curve Key Agreement and Key Transport Protocols."
18. IEEE 1363-2000 (2000) "Standard Specifications for Public-Key Cryptography."
19. ISO/IEC 14888-3 (1998). "Information Technology – Security Techniques – Digital Signatures with Appendix – Part 3: Certificate Based Mechanisms."
20. ISO/IEC 15946 (1999 – Committee Draft). "Information Technology – Security Techniques – Cryptographic Techniques Based on Elliptic Curves."
21. NIST FIPS Pub 186-2 (2000). "Digital Signature Standard."
22. Standards For Efficient Cryptography Group (SECG) (http://www.secg.org) Accessed: 9th July 2012
23. SECG SEC 1 Version 2.0 (2009). "SEC 1: Elliptic Curve Cryptography."
24. SECG SEC 2 Version 2.0 (2010). "SEC 2: Recommended Elliptic Curve Domain Parameters."
25. Certicom (http://www.certicom.com) Accessed: 9th July 2012
26. McGrew, D. (IETF) (2009-Working Draft). "Fundamental Elliptic Curve Cryptography Algorithms." (http://tools.ietf.org/html/draft-mcgrew-fundamental-ecc-01) Accessed: 15th May 2012
27. Koblitz, N. (2010) "My Last 24 Years in Crypto: A Few Good Judgments and Many Bad Ones" (http://2010.eccworkshop.org/slides/Koblitz.pdf) Accessed: 24th June 2012

28. Wikipedia: NIST hash function competition (http://en.wikipedia.org/wiki/NIST_hash_function_competition) Accessed: 12th July 2012

29. Jansma, N., Arrendondo, B. (2004). "Performance Comparison of Elliptic Curve and RSA Digital Signatures." (http://nicj.net/files/performance_comparison_of_elliptic_curve_and_rsa_digital_signatures.pdf) Accessed 12th July 2012

30. Oracle Labs: FAQ (related to ECC) (https://labs.oracle.com/projects/crypto/FrequenlyAskedQuestions.html) Accessed: 12th July 2012

31. SECG X.509 WG Working Group Draft Version 0.2 (1999). "ECC in X.509."

32. Antipa, A., Brown, D., Gallant, R., Lambert, R., Struik, R., Vanstone, S. (2005). "Accelerated Verification of ECDSA Signatures." (http://www.mathnet.or.kr/mathnet/preprint_file/cacr/2005/cacr2005-28.pdf) Accessed: 14th July 2012