An Investigation of Security In Near Field Communication Systems

by

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Abstract

Increasingly, goods and services are purchased over the Internet without any form of physical currency. This practice, often called e-commerce, offers sellers and buyers a convenient way to trade globally as no physical currency must change hands and buyers from anywhere in the world can browse online store fronts from around the globe. Nevertheless, many transactions still require a physical presence. For these sorts of transactions, a new technology called Near Field Communication has emerged to provide buyers with some of the conveniences of e-commerce while still allowing them to purchase goods locally.

Near Field Communication (NFC), an evolution of Radio-Frequency Identification (RFID), allows one electronic device to transmit short messages to another nearby device. A buyer can store his or her payment information on a tag and a cashier can retrieve that information with an appropriate reader. Advanced devices can store payment information for multiple credit and debit cards as well as gift cards and other credentials. By consolidating all of these payment forms into a single device, the buyer has fewer objects to carry with her. Further, proper implementation of such a device can offer increased security over plastic cards in the form of advanced encryption.

Using a testing platform consisting of commercial, off-the-shelf components, this dissertation investigates the security of the NFC physical-layer protocols as well as the primary NFC security protocol, NFC-SEC. In addition, it analyzes a situation in which the NFC protocols appear to break, potentially compromising sensitive data. Finally, this dissertation provides a proof of security for the NFC-SEC-1 variation of NFC-SEC.

Acknowledgements

First, I must thank Professor Alex Wyglinski, who served as my primary advisor for both of my graduate degrees at WPI and who read through numerous drafts of every paper that I have written and provided great feedback each time. He also knows pretty much everybody and his connections were invaluable for tracking down additional support. Plus, he helped me to find my current job. Thanks, Professor!

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To MIT Lincoln Laboratory and LinQuest, thank you for supporting me for the past few years as I worked to complete my PhD and for your understanding when my schedule was not quite normal.

To Isaac, Drew, Zebs, Zach, Ben, Allison, Andrea, Tim, Soe San, Tom, Mike, and anyone else that I've forgotten to list here, thank you for making my time at WPI awesome. You all were always there to distract me from getting work done and to ensure that I did not lose my mind. Thanks!

My parents, my sister, and Jamie: Hey, I finished. Please don't call me Dr. Steve. And also, thanks for everything. Really.

Finally, thanks to Jennifer. You're the best! I totally wouldn't have finished without you. I love you. <3

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Chapter 1

Introduction

1.1 Research Motivation

For at least 150,000 years, people have engaged in trade and commerce. Early humans bartered goods and services directly. As early as 12,000 BCE, civilizations in the Mediterranean region traded with obsidian [1]. By 9,000 BCE, cattle and grain were common forms of money [2]. Cowrie shells were used in China as early as 1,200 BCE [2]. The first coins appeared in Lydia (present day Turkey) in 687 BCE [2]. While these first coins were made from electrum, future coins would be made of bronze, silver, gold, and other metals. Paper money was first introduced in Song dynasty China in 1024 CE [3].

Today, we have many methods of paying for goods and services. Some transactions still use coins and bank notes. Others use checks, money orders, and other forms of guarantees. Still others use credit cards and debit cards. Increasingly, goods and services are purchased over the Internet without any form of physical currency. This practice, sometimes called e-commerce [4], offers sellers and buyers a convenient way to trade globally as no physical currency must change hands and buyers from anywhere in the world can browse online store fronts from around the globe.

Nevertheless, many transactions still require a physical presence. A driver still purchases gasoline for his automobile at gas stations, a thirsty athlete might buy a bottle of water from a vending machine, and the older couple with the convenience store down the road probably doesn't have an online presence. For these sorts of transactions, a new technology called Near Field Communication has emerged to provide buyers with some of the conveniences of e-commerce while still allowing them to purchase goods locally.

Near Field Communication (NFC) allows one electronic device to transmit short messages to another nearby device. As an evolution of Radio-Frequency Identification (RFID), NFC also allows such a device to read passive tags. These tags might contain web addresses, images, product information, or other forms of data. Specifically for financial transactions, these tags can hold payment credentials. Thus, a buyer can store his or her payment information on a tag and a cashier can retrieve that information with an appropriate reader. Advanced devices can store payment information for multiple credit and debit cards as well as gift cards and other credentials. By consolidating all of these payment forms into a single device, the buyer has fewer objects to carry with her. Further, proper implementation of such a device can offer increased security over plastic cards in the form of advanced encryption.

1.2 Current State of the Art

Today, Near Field Communication is used in a wide variety of applications all over the world, including parking meters [5], event ticketing [6][7], public transportation [8][9], hotel keys [10], and in-store payments [11][12][13]. Major credit card companies in the United States have NFC-enabled devices and payment terminals (*e.g.* payWave for Visa [14], PayPass for MasterCard [15]). Google has developed an application called Google Wallet [16] that enables users to store credit card information on their phones and then use those phones to pay at MasterCard PayPass terminals. BlackBerry OS [17] and Windows Phone 8 [18] have similar applications.

Support for NFC in mobile phones is increasingly common in the United States and elsewhere. Google has added NFC support to its Android operating system and many device manufacturers have enabled the feature, including HTC [19], Samsung [20], Motorola [21], and LG Electronics [22]. Many of Research in Motion's BlackBerry phones support the technology [23], as do some Windows phones [24]. While most NFC-enabled phones are smart phones, some feature phones also have support for NFC, most notably the Nokia 6131 flip phone, which was the first mass market mobile phone with built-in support [25]. As of late 2014, Apple's iPhone supports NFC transactions only in a very limited form called Apple Pay.

1.3 Research Objectives

While Near Field Communication provides many advantages that traditional payment methods lack, it also has drawbacks. For instance, storing multiple payment credentials into a single NFC-enabled device produces a single point of failure. Should the NFC-enabled device be lost or stolen, so too are all of those payment credentials lost. Perhaps the biggest potential disadvantage to using NFC over other payment methods is that NFC devices transmit data wirelessly. Wireless transmissions tend to be vulnerable to a number of malicious attacks, including eavesdropping and relay attacks. With this in mind, the primary research objectives of this dissertation are the following:

- To provide a comprehensive overview of Near Field Communication technology, public key cryptography, and other technologies related to NFC mobile payment applications.
- To build a testing platform using commonly available hardware and software that is capable of emulating realistic NFC transactions.
- To utilize the testing platform to investigate security vulnerabilities in the most commonly implemented NFC protocols and specifications, including NFCIP-1 and NFC-SEC.

1.4 Contributions

In order to complete the tasks described in Section 1.3, this dissertation makes the following novel contributions:

- *A comprehensive overview* of the vulnerabilities inherent to NFC transactions, the current state of research toward exploiting those vulnerabilities, and defenses built into the NFC protocols to thwart them.

- *A testing platform* that includes microprocessors, NFC controllers, and other hardware and software commonly found in widely-used mobile devices. This testing platform allows users to investigate a variety of NFC devices and software combinations for protocol correctness and vulnerabilities.
- *An investigation* into a flaw in the NFC single-device detection protocol that exposes NFC transactions to numerous security problems, including spoofed data and denial of service attacks.
- *A proof of security* for the NFC-SEC-1 SSE security protocol, used to establish a secure channel in the absence of hardware secure elements (*e.g.* SIM cards) using Protocol Composition Logic.

A list of publications resulting from this work can be found in Section 8.3.

1.5 Dissertation Organization

The remainder of this dissertation is organized as follows: Chapter 2 provides detailed descriptions of Near Field Communication technology and Chapter 3 describes the encryption systems employed by NFC devices; Chapter 4 contains a thorough overview of the current state of research into exploiting NFC transactions; Chapter 5 describes the hardware, software, and operation of the testing NFC platform; Chapter 6 details a vulnerability in the NFC single-device detection protocol; Chapter 7 examines the NFC-SEC protocol with Protocol Compositioon Logic and offers a proof for NFC-SEC-1 SSE; finally, Chapter 8 offers concluding remarks and directions for future research. Appendix A describes an algorithm for multiplying integers in certain finite fields.

Chapter 2

Near Field Communication

This chapter provides an introduction to the near field communication (NFC) technology used in this dissertation, including a brief overview and history of the technology and a detailed primer on its operation.

2.1 Overview

Near Field Communication (NFC) technology is fairly new, having first been published as a standard by Ecma International as ECMA-340 in December, 2002 [27]. Building upon the ideas established by Radio Frequency Identification (RFID), NFC devices use short-range radio communication to transfer information. While RFID allowed one-way communication (*e.g.*, a smart phone reading a passive smart tag), NFC additionally allows two-way communication (*e.g.*, two smart phones exchanging information). Like many RFID devices, NFC devices operate in the 13.56 MHz industrial, scientific, and medical (ISM) band, which is unlicensed worldwide. The operating range of NFC devices is typically less than five centimeters. Table 2.1 compares NFC technology with some other popular wireless technologies.

In 2004, the International Organization of Standardization (ISO) and the International Electrotechnical Commission (IEC) published a revised version of this standard as ISO/IEC

Parts of this Chapter were submitted for publication to Wiley Journal on Wireless Communications and Networks [26].

Table 2.1: Comparison of popular wireless technologies.

	NFC [28]	Bluetooth [29]	WiFi [30]	ZigBee [31]
Base Standard	ISO/IEC 18092	Bluetooth SIG	IEEE 802.11	IEEE 802.15.4
Max Bit Rate	424 Kbps	2.1 Mbps	7 Gbps	250 Kbps
Typical Range	<5 cm	<100m	<100m	<100m
Network Type	Point-to-Point	Wireless PAN	Wireless LAN	Wireless PAN
Frequency	13.56 MHz	2.4 GHz	2.4 GHz, 5 GHz	2.4 GHz, 915 MHz, 868 MHz

18092:2004 [32]. Since then, both standards have been amended and revised. The most recent versions were published in June, 2013 as ECMA-340 3$^{\text{rd}}$ Edition [33] and ISO/IEC 18092:2013 [28]. In 2004, NXP Semiconductors, Sony, Nokia, and others founded the NFC Forum, a non-profit industry association whose mission is to advance the use of NFC technology. Today, the NFC Forum has more than 190 member organizations [34]. The NFC Forum is responsible for a number of additional standards, including standards for message formats and device characteristics.

2.2 Physical Operation

The name "Near Field Communication" comes from the fact that NFC devices communicate in the electromagnetic near field. That is, two NFC devices can communicate when they are separated by a distance of less than one wavelength (λ). In fact, NFC devices operate within an even smaller region called the reactive near field, in which which they are less than ${}^{\lambda}/_{2\pi}$ apart. Figure 2.1 shows the division of the near and far field regions. A quick calculation would show that the reactive near field for devices operating at 13.56 MHz is approximately 3.52 meters. However, that is only true for an antenna of length ${}^{\lambda}/_{2}$, which would be approximately 11 m. Since NFC is most frequently found in mobile devices, such an antenna length is not practical. The NFC specifications aim for an operating range of approximately 4-10 cm, which allows for much smaller antennas.

In the reactive near field, some energy is held near the surface of the antenna. For

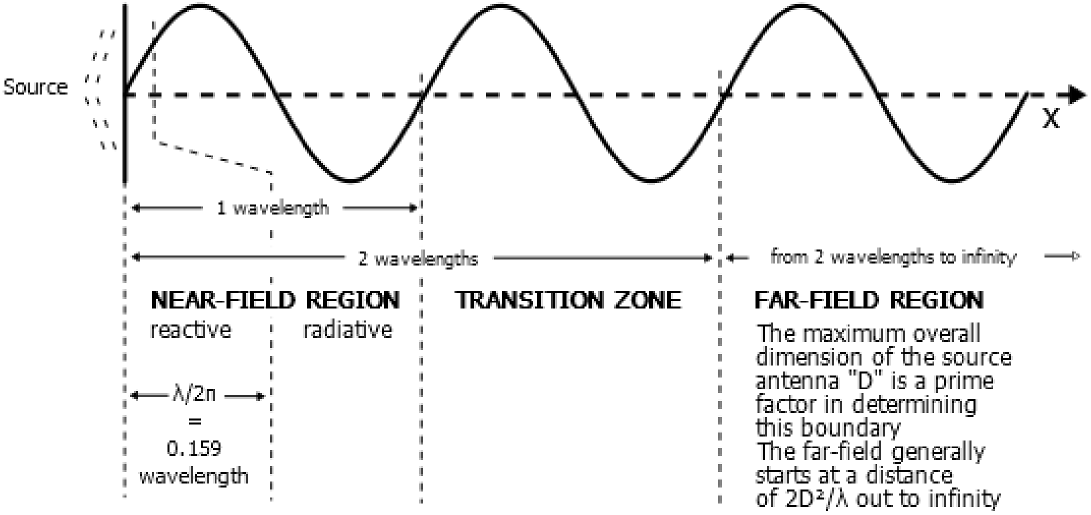

Source
X
1 wavelength
2 wavelengths
from 2 wavelengths to infinity
NEAR-FIELD REGION
reactive
radiative
TRANSITION ZONE
FAR-FIELD REGION
The maximum overall dimension of the source antenna "D" is a prime factor in determining this boundary
The far-field generally starts at a distance of 2D²/λ out to infinity
λ/2π = 0.159 wavelength

Figure 2.1: Regions of an EM field. NFC operates in the reactive near field region [35].

instance, an alternating current flowing through a transmitting antenna creates a magnetic field near the antenna. When the current reverses direction, this magnetic field collapses and returns the energy to the electrons in the antenna. However, if a receiving device absorbs some of this magnetic energy, then that energy is lost to the transmitting antenna. This loss changes the impedance of the transmitting antenna, which can be sensed as a small change in the voltage across a resistor in series with that antenna [36].

NFC devices employ loop antennas. When two devices are in operating range, the combination of the two antennas acts like a transformer, where the current flowing through the transmitting antenna creates an electromagnetic field, which induces a current in the receiving device antenna. The receiving device powers itself with this current. In contrast to RFID, in which only one device may generate an electromagnetic field, both NFC devices are allowed to generate an EM field. However, only one device does so at any time. Figure 2.2 shows the relationship between two NFC devices when initiating a transaction.

If both devices are "active" devices, then data flows in the same direction as the EM field. When the Initiator device has finished transmitting data, it turns off its EM field. When the Target is ready to respond, it turns on its own EM field and sends data back to

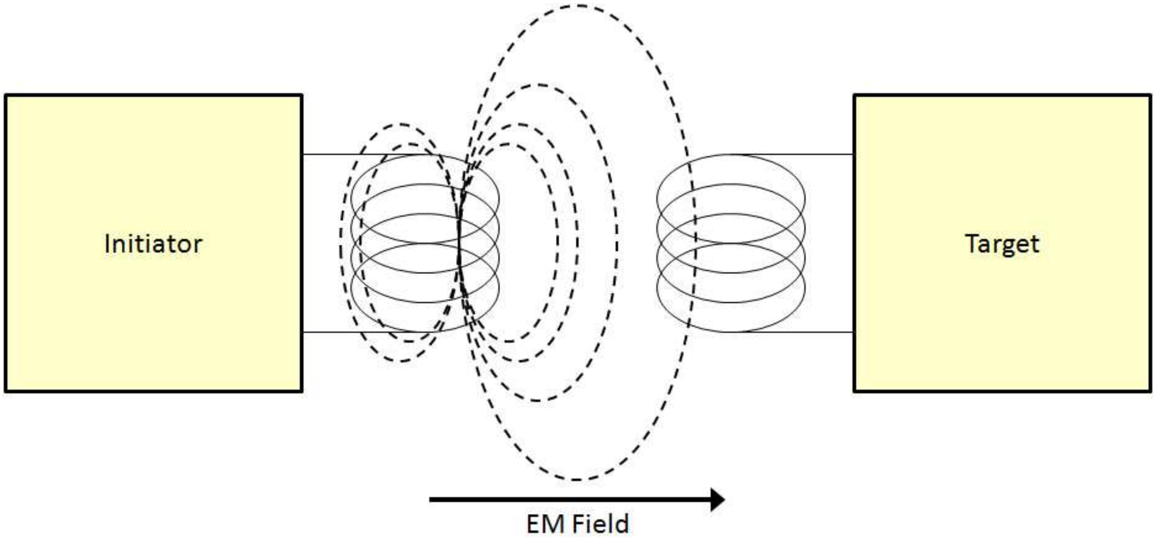


Figure 2.2: Magnetic induction with two NFC devices. The two coils represent the loop antennas on the NFC devices and the dashed rings represent the EM field. Here, the Initiator generates the field to power the Target.

the Initiator. Like RFID, NFC also supports “passive” Target devices. If the Target is a passive device, then it always uses the Initiator’s EM field for power and modulates that field to send data back to the Initiator.

2.3 Protocol

The ISO/IEC, ECMA, and NFC Forum maintain numerous standards defining NFC protocols. As with many other communications technologies, these protocols are layered atop one another. Figure 2.3 compares the various NFC layers [37] with those of the Open Systems Interconnection (OSI) model defined in the ISO/IEC 7498-1 standard [38] and with the commonly-used TCP/IP stack [39]. Since NFC devices typically communicate in a point-to-point fashion, there is no need for the session (*e.g.*, sockets), transport (*e.g.*, TCP), and network (*e.g.*, IP) layers.

The following subsections deal with each layer in the NFC Forum stack, starting with the lowest layer.

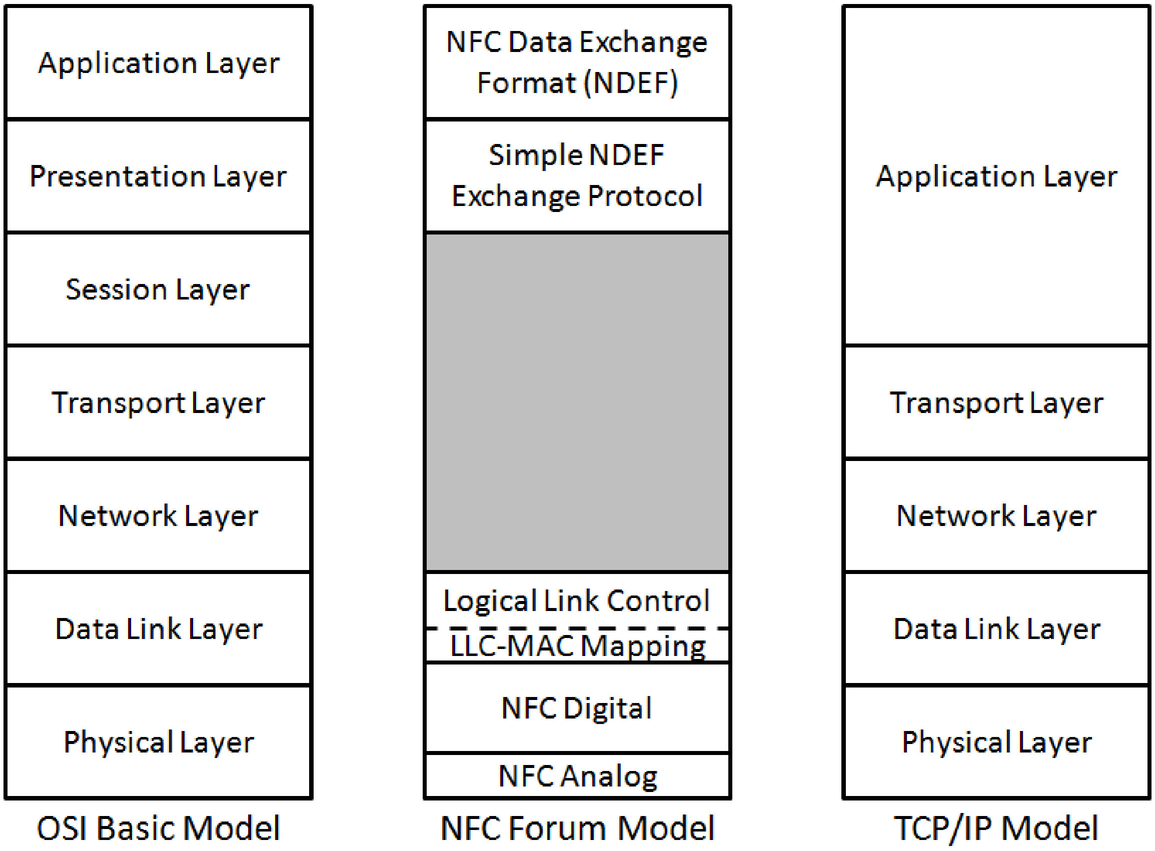


Figure 2.3: Structure of the NFC protocol layers. Compared to the OSI and TCP/IP models, the NFC model has no layers for networking with more than two devices. The NFC Analog and NFC Digital layers in NFC Forum devices expand upon NFCIP-1, while the higher layers are only defined for NFC Forum devices.

2.3.1 Analog Interface

The Near Field Communication Interface and Protocol (NFCIP-1) standard (ECMA-340 [33], ISO/IEC 18092:2013[28]) defines the analog interface for NFC devices. The NFC Forum's ANALOG [36] specification further defines the analog interface and includes multiple types of NFC and NFC-compatible devices. One common device type is the ISO/IEC 14443 proximity card [40] and, indeed, much of the NFC analog standard is based on the ISO/IEC 14443 radio interface standard. As a result, NFC devices are capable of reading such proximity cards. Notable examples of these cards include NXP Semiconductor's MIFARE [41], biometric passports [42], and EMV payment cards [43].

Table 2.2: Modulation and coding schemes used for NFC.

Device Mode	Data Rate	Encoding	Modulation
Active	$^{f_c}/_{128}$ (∼106 Kbps)	Modified Miller	ASK 100%
Passive	$^{f_c}/_{128}$ (∼106 Kbps)	Manchester	ASK 10%
Active	$^{f_c}/_{64}$ (∼212 Kbps)	Manchester	ASK 10%
Passive	$^{f_c}/_{64}$ (∼212 Kbps)	Manchester	ASK 10%
Active	$^{f_c}/_{32}$ (∼424 Kbps)	Manchester	ASK 10%
Passive	$^{f_c}/_{32}$ (∼424 Kbps)	Manchester	ASK 10%

All NFC devices operate on the 13.56 MHz carrier frequency (f_c) and support three data rates: $^{f_c}/_{128}$, $^{f_c}/_{64}$, and $^{f_c}/_{32}$, or approximately 106 Kbps, 212 Kbps, and 424 Kbps. The modulation and coding schemes employed by an NFC device depends on whether it is "active" or "passive", and on what data rate it is using. Table 2.2 summarizes the different modulation schemes used by NFC devices [40][33].

An active device uses amplitude shift keying (ASK) to modulate its EM field when transmitting data to another device. Two levels of ASK are supported. At a data rate of $^{f_c}/_{128}$, the device uses a 100% scheme such that a high level is the default EM field strength and a low level has less than 5% of that strength. Otherwise, the device uses a 10% scheme, where a high level is the default EM field strength and a low level is approximately 82% of that strength. Passive devices employ load modulation in order to generate a subcarrier with a frequency (f_s) of $^{f_c}/_{16}$ (∼848 KHz) [40]. The subcarrier is modulated with a 10% ASK scheme.

As with modulation, the encoding employed by an NFC device varies. Active devices, both Initiators and Targets, use a modifier Miller coding scheme at a data rate of $^{f_c}/_{128}$. This scheme defines three sequences, as shown in Figure 2.4. The NFCIP-1 standard uses these sequences in the following manner [40]:

- For a logic '1', use Sequence X,

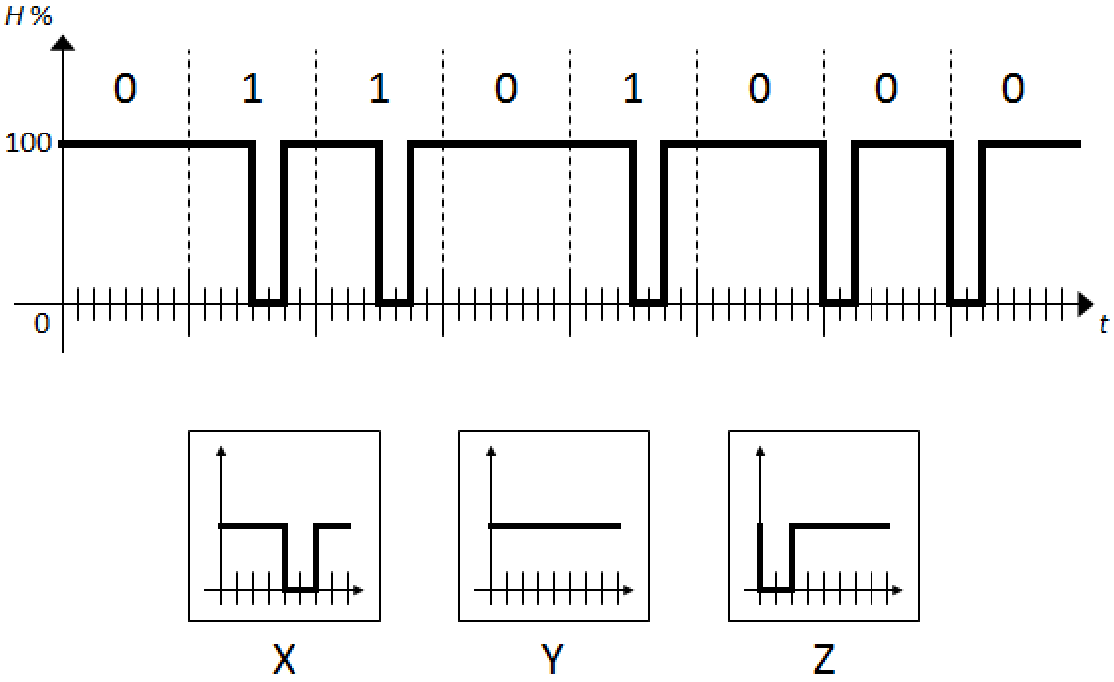


Figure 2.4: Plot of the modified miller encoding of the ASCII letter ‘h’. The dashed lines mark the bit periods. This plot assumes that the bit prior to time zero was not a logic ‘0’ or a “start of communication” bit. Note that there are eight periods of the subcarrier in each bit period and that the subcarrier is modulated with on-off keying (OOK), or ASK 100%.

- For a logic ‘0’, use Sequence Y, except:
    - For two or more contiguous ‘0’s, use Sequence Z for all but the first,
    - For a logic ‘0’ after the “start of communication”, use Sequence Z,
- For “start of communication”, use Sequence Z,
- For “end of communication”, use a logic ‘0’ followed by Sequence Y.
- For “no information”, use two or more Sequence Ys.

For active devices using a date rate of ${}^{f_c}/_{64}$ or ${}^{f_c}/_{32}$ and for all passive devices, NFCIP-1 mandates a Manchester encoding. Passive devices operating at a bit rate of ${}^{f_c}/_{128}$ use on-off keying (OOK), while all devices operating at ${}^{f_c}/_{64}$ or ${}^{f_c}/_{32}$ use an alternative Manchester

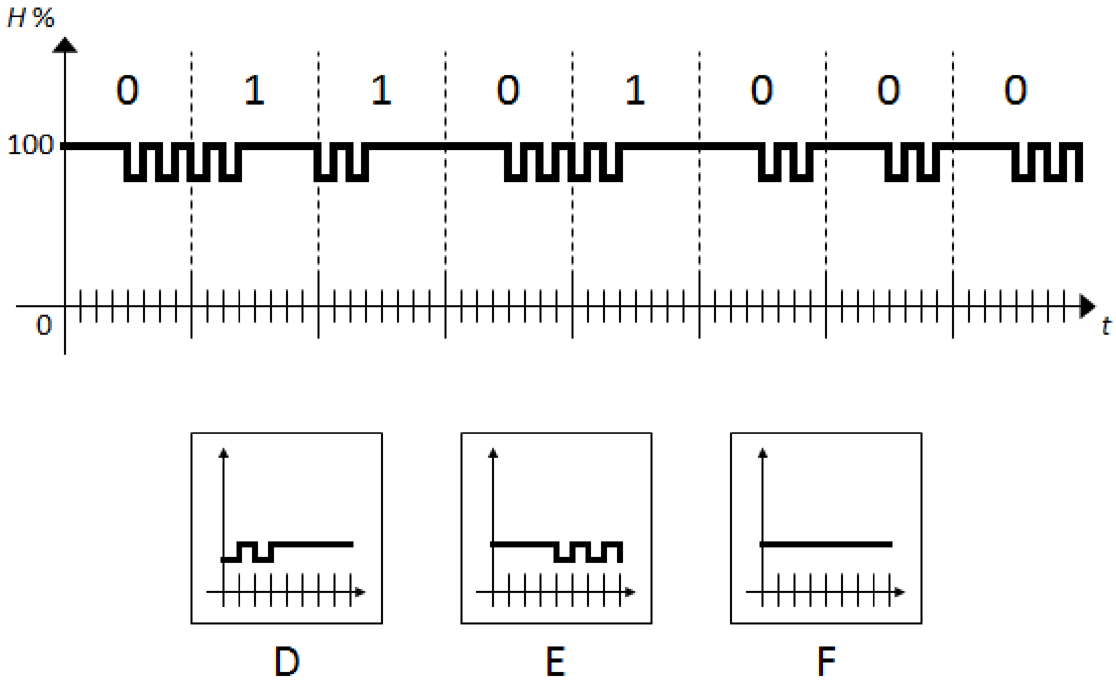


Figure 2.5: Plot of the Manchester encoding of the ASCII letter ‘h’ for passive devices operating at ${}^{f_c}/_{128}$. The dashed lines mark the bit periods. Note that there are eight periods of the subcarrier in each bit period and that the subcarrier is modulated with ASK 10%, so the lower field strength is 82% of the maximum.

scheme. Figure 2.5 illustrates the former scheme, with sequences D, E, and F defined as follows [40]:

- For a logic ‘1’, use Sequence D,
- For a logic ‘0’, use Sequence E,
- For “start of communication”, use Sequence D,
- For “end of communication”, use Sequence F,
- For “no information”, use no subcarrier

Figure 2.6 illustrates the scheme for devices operating at ${}^{f_c}/_{64}$ or ${}^{f_c}/_{32}$ [33]. The NFCIP-1 standard allows for a polar reversal of Figure 2.6 and polarity is determined during the SYNC transmission (see Section 2.3.2).

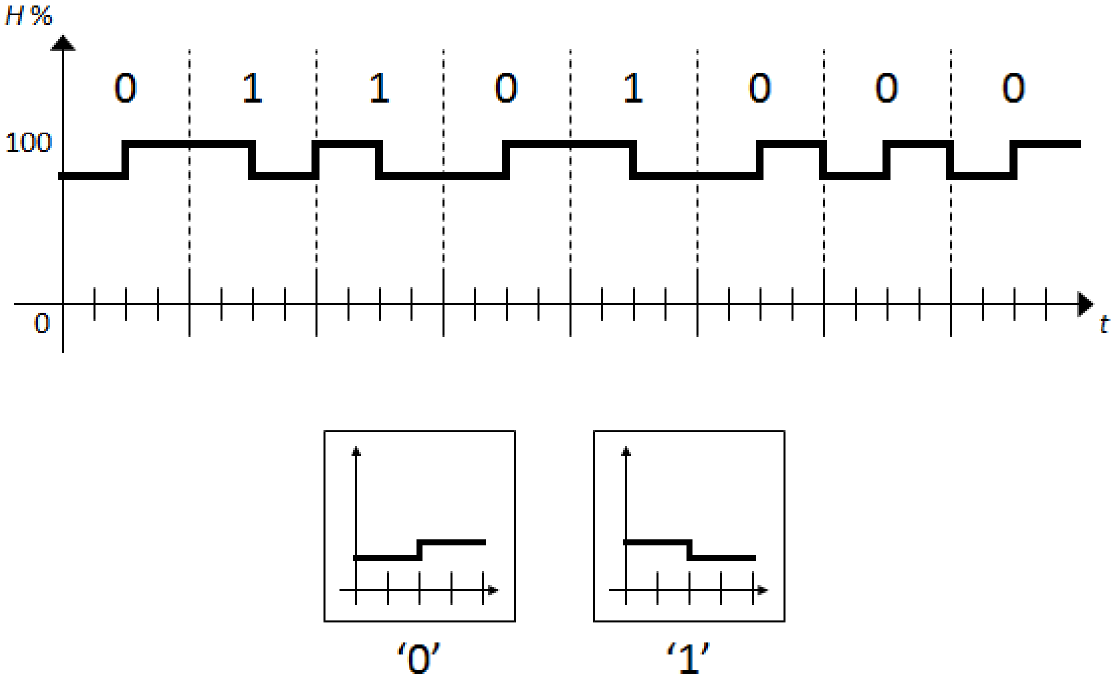


Figure 2.6: Plot of the Manchester encoding of the ASCII letter 'h' for devices operating at $^{f_c}/_{64}$ or $^{f_c}/_{32}$. The dashed lines mark the bit periods. Each bit period in this Figure is equal to $4 * f_s$, so the data rate is $^{f_c}/_{64}$. A device operating at $^{f_c}/_{32}$ would have bit periods of $2 * f_s$. Note that each bit is modulated with ASK 10%, so the lower field strength is 82% of the maximum.

Finally, note that devices operating at $^{f_c}/_{128}$ transmit bytes with the least-significant bit first and that devices operating at $^{f_c}/_{64}$ or $^{f_c}/_{32}$ transmit bytes with the most-significant bit first.

2.3.2 Digital Interface

The second layer in the stack, the Digital Interface, is defined by the NFCIP-1 standard (ECMA-340 [33], ISO/IEC 18092:2013 [28]) and is further expanded upon by the NFC Forum's DIGITAL specification [44]. These standards are partially based on the ISO/IEC 14443-3:2011 standard [45] for proximity cards. The Digital Interface has two primary responsibilities: device detection and initialization, and data exchange. Figure 2.7 shows the flow of a NFC transaction in both the active and passive modes.

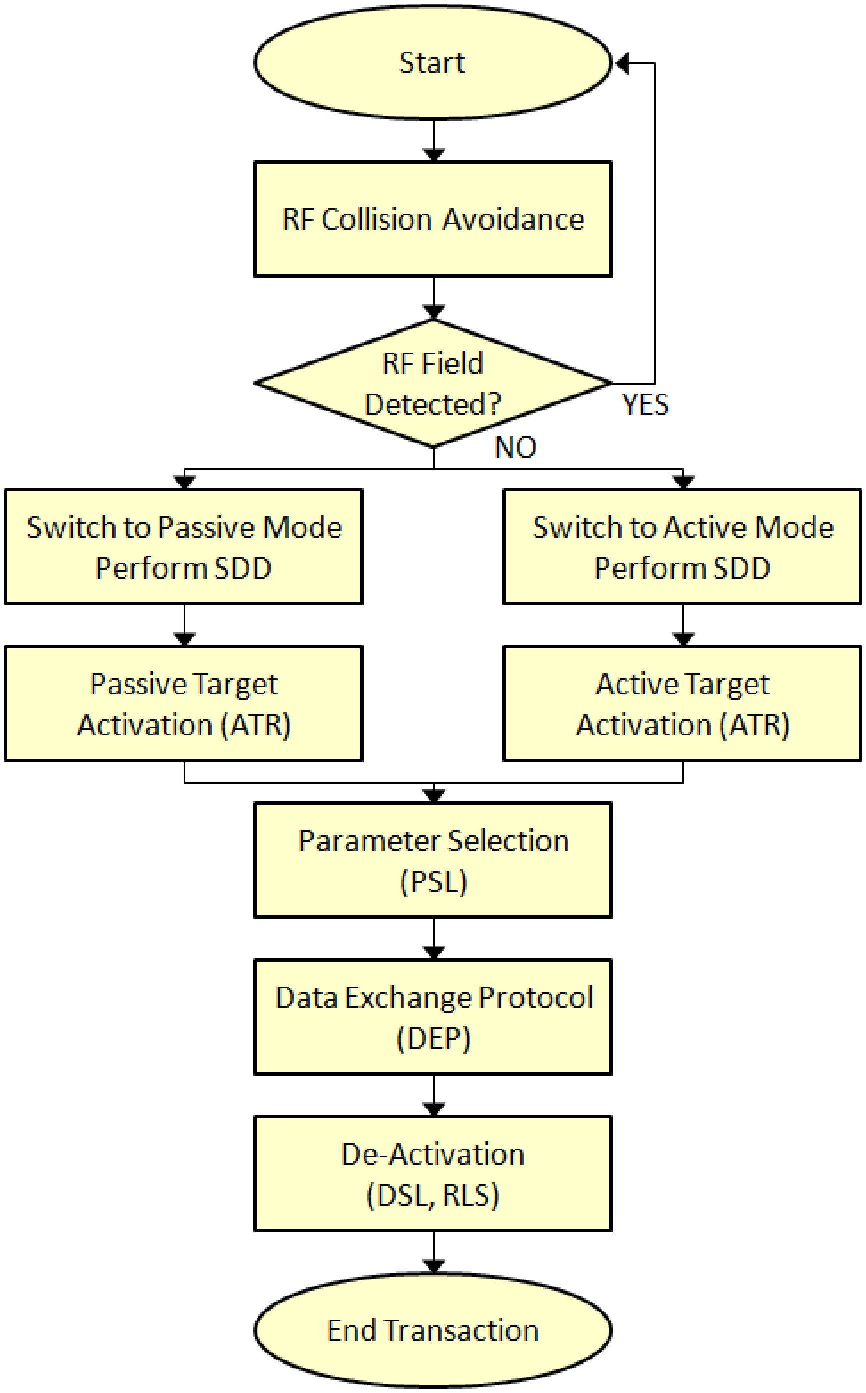

Start
RF Collision Avoidance
RF Field Detected?
YES
NO
Switch to Passive Mode Perform SDD
Switch to Active Mode Perform SDD
Passive Target Activation (ATR)
Active Target Activation (ATR)
Parameter Selection (PSL)
Data Exchange Protocol (DEP)
De-Activation (DSL, RLS)
End Transaction

Figure 2.7: Flowchart of a NFC transaction. The Initiator determines the data rate after switching to the appropriate communication mode, but before activating the Target [33].

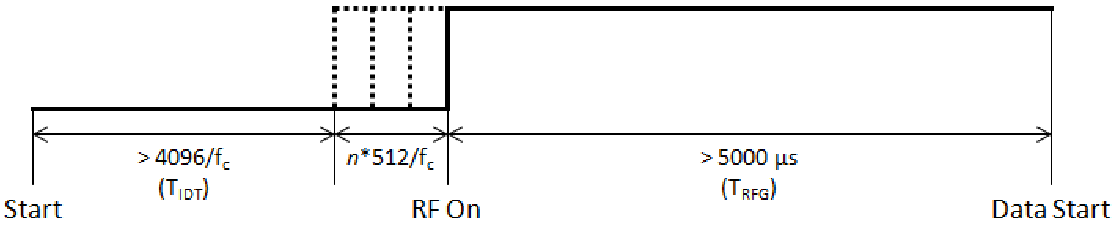


Figure 2.8: Timing of the Initial RF Collision Avoidance algorithm. The Initiator randomly chooses the value of n in the range 0–3. In this diagram, the value is 3. As always, the value of f_c is 13.56 MHz. This Figure is not to scale [33].

2.3.2.1 Single Device Detection and Initialization

In order to prevent interference with other devices operating in the 13.56 MHz frequency band, a NFC device will not switch on its EM field if it detects another EM field with a strength of at least 0.1875 A/m (rms). The “Initial RF Collision Avoidance” protocol is illustrated in Figure 2.8. When the Initiator needs to activate its EM field to begin a transaction, it first chooses a random integer value in the range 0–3. If the device detects no EM field after $T_{IDT} + n * 512/f_c$ seconds, where $T_{IDT} = 4096 * f_c$, then it switches its EM field. Otherwise, the device begins the algorithm again. The shortest possible wait time for an Initiator to switch on its EM field is approximately 350 µs, though it must wait at least another $T_{RFG} = 5,000$ µs to begin sending data.

The single device detection and device initialization algorithms are different for devices using active mode than for devices using passive mode.

Active Mode — Target devices in the active communication mode perform an algorithm similar to the Initiator’s “Initial RF Collision Avoidance” algorithm. Once the Target has received the first command from the Target, it waits at least $T_{ADT} + n * 512/f_c$ seconds before switching on its EM field, where T_{ADT} is at least $768/f_c$, but not more than $2,559/f_c$ and n is again a randomly chosen integer in the range 0–3. This wait provides the Initiator time to switch off its EM field. Once the Target has switched on its EM field, it must wait at least $T_{ARFG} = 1024/f_c$ seconds before sending the response. Since n is random, not all Targets will respond to the Initiator’s command at the same time. The Target in range with the lowest value for n will respond first and the other devices will not respond at all.

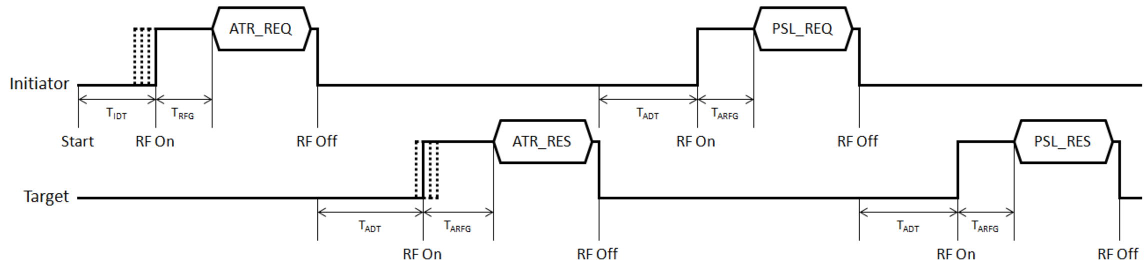


Figure 2.9: Timing of the initial active mode device configuration. Here, the Initiator activates the Target and requests to change some parameters. The Target responds to both commands. Next, the Initiator could begin using the Data Exchange Protocol [33].

If more than one Target device responds at the same time, then the Initiator will detect a data collision and start the process again. This process continues until only one Target responds. After a Target is activated, the Initiator and Target both use $n = 0$ and the Target's RF collision avoidance algorithm for further communications.

In the active communication mode, the Initiator first sends the attribute request command (ATR_REQ) and the Target responds with the attribute response (ATR_RES). Next, the Initiator can choose to change some communication parameters, such as the data rate and maximum frame length, by sending the parameter select request (PSL_REQ), which the Target answers with a parameter select response (PSL_RES), or enter the data exchange protocol by sending a data exchange protocol request (DEP_REQ), which the Target answers with a data exchange protocol response (DEP_RES). These commands are further defined in Section 2.3.2.2. Figure 2.9 shows the initialization process for active mode communication. Following the PSL_RES, the Initiator would likely issue a DEP_REQ to begin data exchange.

Passive Mode — For devices operating in the passive communication mode, there are two different algorithms for single device detection and device configuration. The first is a modified version of the algorithm described in ISO/IEC 14443-3:2011 [45] and is used for devices operating at $^{f_c}/_{128}$, which the NFC Forum standards call NFC-A, and the second applies to devices operating at $^{f_c}/_{64}$ or $^{f_c}/_{32}$, called NFC-F. In all cases, the Initiator's EM field remains switched on for the duration of the transaction and the Target, being passive,

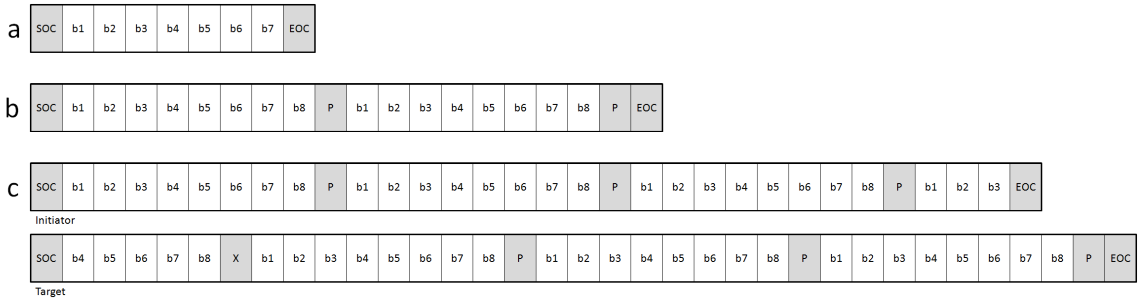

a
SOC b1 b2 b3 b4 b5 b6 b7 EOC
b
SOC b1 b2 b3 b4 b5 b6 b7 b8 P b1 b2 b3 b4 b5 b6 b7 b8 P EOC
c
SOC b1 b2 b3 b4 b5 b6 b7 b8 P b1 b2 b3 b4 b5 b6 b7 b8 P b1 b2 b3 b4 b5 b6 b7 b8 P b1 b2 b3 EOC
Initiator
SOC b4 b5 b6 b7 b8 X b1 b2 b3 b4 b5 b6 b7 b8 P b1 b2 b3 b4 b5 b6 b7 b8 P b1 b2 b3 b4 b5 b6 b7 b8 P EOC
Target

Figure 2.10: a) A short frame, used for starting communication. b) A standard frame, used for most commands. Standard frames can have $n \geq 1$ bytes and each byte has odd parity, P. This Figure shows a frame with 2 bytes. c) A bit-oriented frame used for single-device detection. Here, the Initiator sends three full bytes and three additional bits; the Target sends the remaining five bits of that byte and then three more full bytes. The total number of bits in a bit-oriented frame is always 56, but the split can occur anywhere. If the split occurs mid-byte, as it does in this Figure, then the parity bit for the split byte is ignored.

never generates its own field.

NFC-A Devices — The first algorithm, used for devices operating at ${}^{f_c}/_{128}$ in passive mode, employs three types of frames, as shown in Figure 2.10. Short frames are used to begin transactions, bit-oriented SDD frames are used for the single-device detection algorithm, and standard frames are used for all other commands and data. All frames are transmitted in pairs so that each request from the Initiator is paired with a response from the Target. The time that the Target must wait before sending a response depends on the request that the Initiator sent. For the commands used in the anti-collision algorithm, devices must use a value of $1236/f_c$ so that they respond synchronously. For other commands, the delay can be longer, but not shorter. The time that the Initiator waits after receiving a response is at least $1772/f_c$.

The first command that the Initiator sends is sense request (SENS_REQ), a short frame, which all Target devices in range answer with sense response (SENS_RES), a standard frame of two bytes. If only one device responds, then the Initiator sends out a single-device detection request (SDD_REQ) to get the device's unique ID (NFCID1). The Target responds with its NFCID1 (SDD_RES). Next, the Initiator sends out a SEL_REQ command with the Target's NFCID1 and the Target responds with a select acknowledge (SAK). If the

Table 2.3: Coding of the SAK frame.

b8	b7	b6	b5	b4	b3	b2	b1	Meaning
X	X	X	X	X	1	X	X	NFCID1 not complete.
X	1	X	X	X	0	X	X	NFCID1 complete, Target supports NFCIP-1, Target supports ATR_REQ.
X	0	X	X	X	0	X	X	NFCID1 complete, Target supports NFCIP-1, Target does not support ATR_REQ.

SAK frame indicates that the NFCID1 is not complete, then this particular Target device has a "double" or "triple" NFCID1 and the Initiator repeats the SDD_REQ command to get the second (and possibly third) part of the NFCID1. The final SAK response indicates that the NFCID is complete. Table 2.3 outlines the possible SAK values for the NFCIP-1 standard.

If more than one device responds to the SENS_REQ command, then the Initiator must perform the anti-collision algorithm. Figure 2.11 shows the flow of this algorithm. First, the Initiator sends the single-device detection request (SDD_REQ), a standard frame with two bytes, and listens for the SDD_RES from each Target. The SSD_RES contains the NFCID1 (or the first part of the NFCID1 for devices with "double" or "triple" NFCID1s). If there is no collision in the SDD_RES frames, then the Initiator asks for the second part of the NFCID1, and continues this process until a collision is found. When a collision is found, the Initiator sends a bit-oriented SDD_REQ frame with the received NFCID1 up to the bit before the collision and '1' appended to the end. This process repeats until there is no collision, at which point the Initiator gets the Target device's full NFCID1, stores it, and then sends a sleep request (SLP_REQ) to remove that device from the process. The Initiator again sends out a two-byte SDD_REQ and repeats the process until it has found all available Target devices.

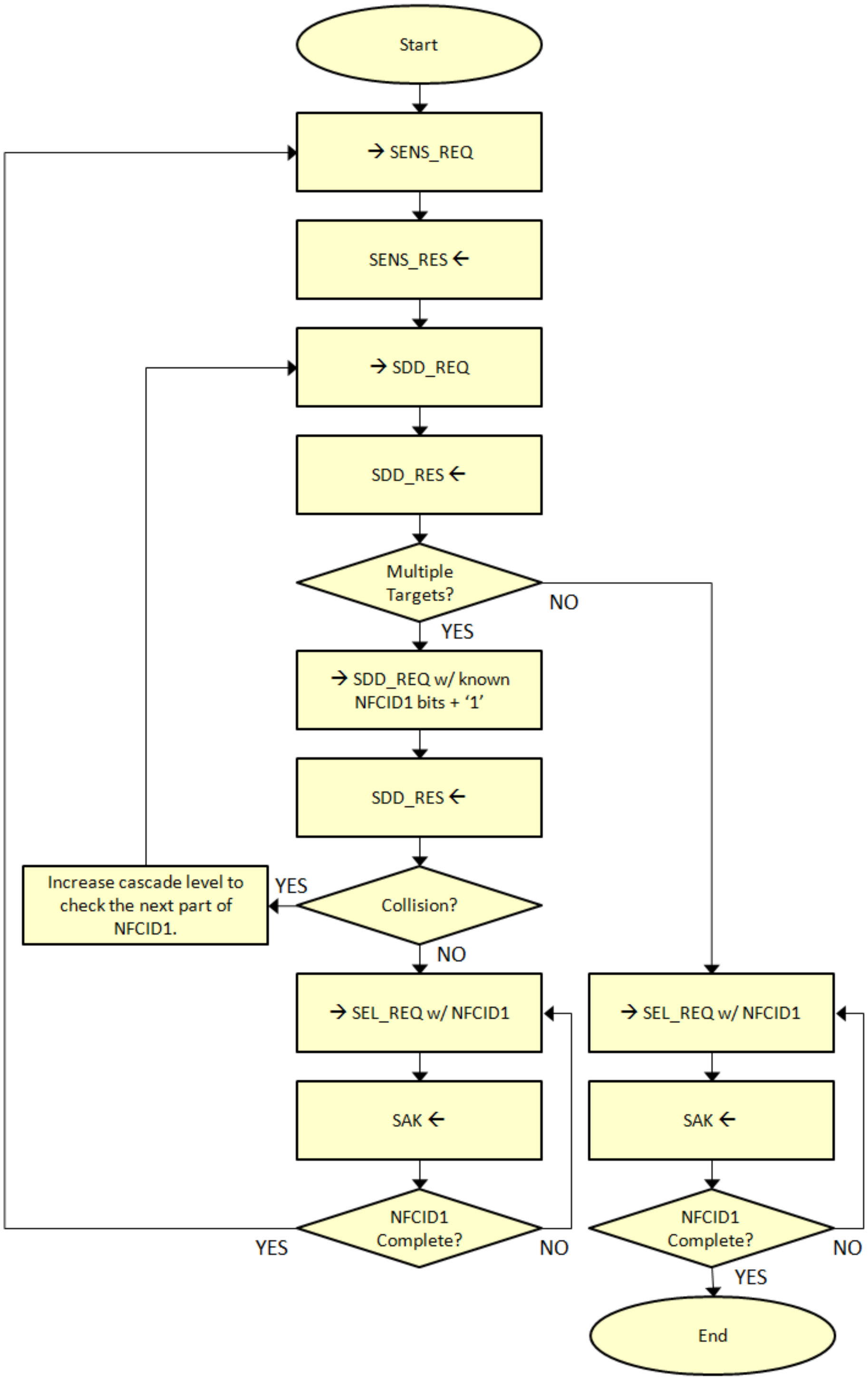


Figure 2.11: Flowchart of the anti-collision algorithm for passive $^{f_c}/_{128}$ devices. Arrows pointing right indicate frames sent by the Initiator and arrows pointing left indicate frames sent by the Target(s) [45][44][46].

Figure 2.12 illustrates the single-device detection algorithm with an example. In this Figure, there are two Target devices. The first has a normal NFCID1 of 50-40-30-20h and the second has a “double” NFCID1 of 80-70-60-50-40-30-20h. The first byte of each SDD_REQ depends on the cascade level where 93h is level one, 95h is level two, and 97h is level three. The upper half of the second byte determines the number of full bytes in the command (not including the CRC) and the lower half determines the number of extra bits sent. The final byte of each SDD_RES is an exclusive-OR of the previous four bytes.

NFC-F Devices — The final anti-collision algorithm applies to passive devices operating at ${}^{f_c}/_{64}$ or ${}^{f_c}/_{32}$. This algorithm uses only one frame format, illustrated in Figure 2.13. The following rules apply to the frames in Figure 2.13:

- The Preamble is at least 48 bits of encoded zeros,
- SYNC can be inverted (4Dh B2h) to use reverse polarity encoding (see Section 2.3.1).
- TSN is 00h, 01h, 03h, 07h, or 0Fh and is the number of time slots to use for the anti-collision algorithm,
- NFCID2 is the eight-byte device ID,
- PAD is an eight-byte padding field, which is ignored,
- CRC is calculated according to A.3 of [44].

In order to detect devices, the Initiator first sends a Polling Request (SENS_REQ) frame with TSN configured for the number of time slots that the Initiator supports. NFC Forum devices conforming to the ACTIVITY specification must use a TSN value of 0Fh [46] when using the anti-collision algorithm, though the value of TSN can be set to 00h to disable the algorithm. A time slot is $16,384/f_c$ seconds long and there is a delay if $32,768/f_c$ seconds between the end of the SENS_REQ frame and the start of the first time slot.

Once the SENS_REQ is finished, each Target device in range generates a random integer value, R, in the range 0–TSN. The Targets then respond with Polling Response (SENS_RES) frames that contain their unique NFCID2 numbers when their time slots arrive. Figure 2.14

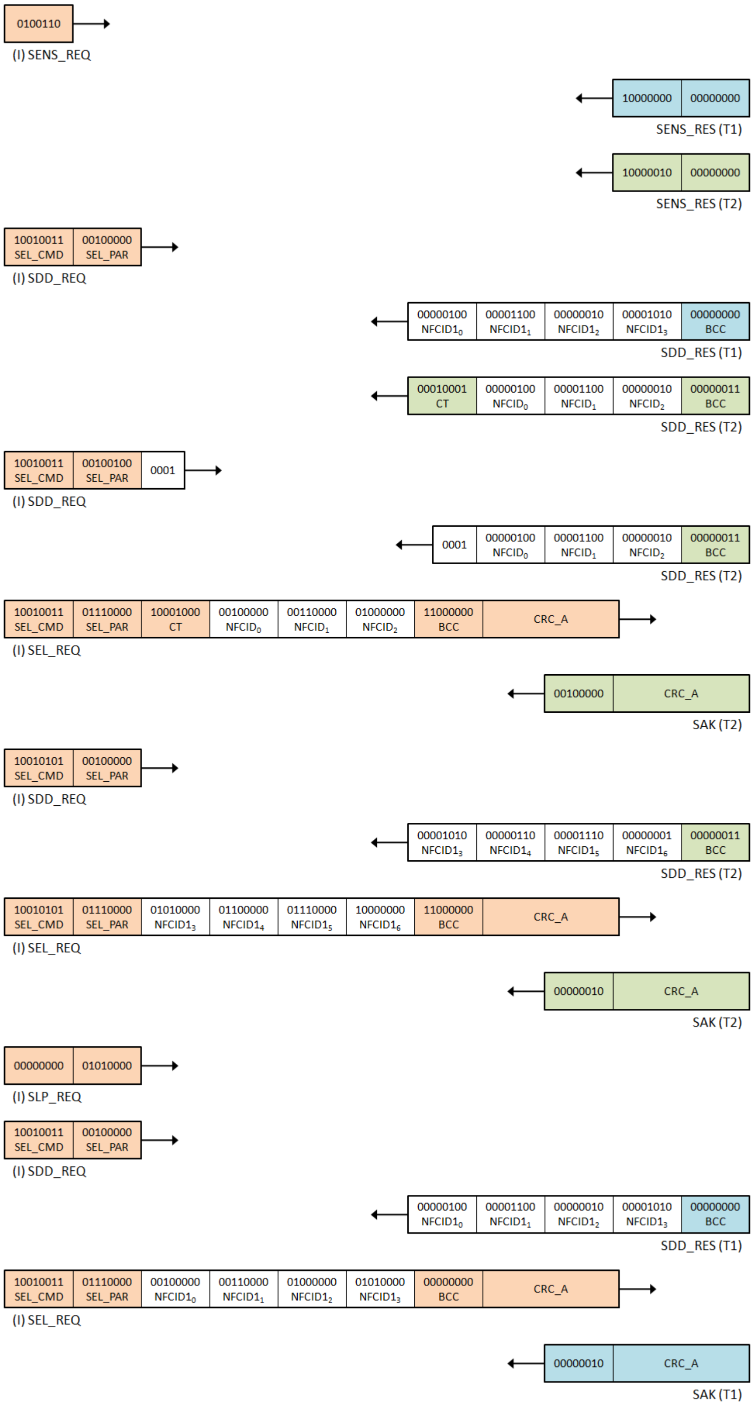

0100110
(I) SENS_REQ
10000000 00000000
SENS_RES (T1)
10000010 00000000
SENS_RES (T2)
10010011 SEL_CMD 00100000 SEL_PAR
(I) SDD_REQ
00000100 NFCID1$_0$ 00001100 NFCID1$_1$ 00000010 NFCID1$_2$ 00001010 NFCID1$_3$ 00000000 BCC
SDD_RES (T1)
00010001 CT 00000100 NFCID$_0$ 00001100 NFCID$_1$ 00000010 NFCID$_2$ 00000011 BCC
SDD_RES (T2)
10010011 SEL_CMD 00100100 SEL_PAR 0001
(I) SDD_REQ
0001 00000100 NFCID$_0$ 00001100 NFCID$_1$ 00000010 NFCID$_2$ 00000011 BCC
SDD_RES (T2)
10010011 SEL_CMD 01110000 SEL_PAR 10001000 CT 00100000 NFCID$_0$ 00110000 NFCID$_1$ 01000000 NFCID$_2$ 11000000 BCC CRC_A
(I) SEL_REQ
00100000 CRC_A
SAK (T2)
10010101 SEL_CMD 00100000 SEL_PAR
(I) SDD_REQ
00001010 NFCID1$_3$ 00000110 NFCID1$_4$ 00001110 NFCID1$_5$ 00000001 NFCID1$_6$ 00000011 BCC
SDD_RES (T2)
10010101 SEL_CMD 01110000 SEL_PAR 01010000 NFCID1$_3$ 01100000 NFCID1$_4$ 01110000 NFCID1$_5$ 10000000 NFCID1$_6$ 11000000 BCC CRC_A
(I) SEL_REQ
00000010 CRC_A
SAK (T2)
00000000 01010000
(I) SLP_REQ
10010011 SEL_CMD 00100000 SEL_PAR
(I) SDD_REQ
00000100 NFCID1$_0$ 00001100 NFCID1$_1$ 00000010 NFCID1$_2$ 00001010 NFCID1$_3$ 00000000 BCC
SDD_RES (T1)
10010011 SEL_CMD 01110000 SEL_PAR 00100000 NFCID1$_0$ 00110000 NFCID1$_1$ 01000000 NFCID1$_2$ 01010000 NFCID1$_3$ 00000000 BCC CRC_A
(I) SEL_REQ
00000010 CRC_A
SAK (T1)

Figure 2.12: Example of the anti-collision algorithm for passive $^{f_c}/_{128}$ devices with two Targets. This Figure does not show SOC, EOC, or parity bits. For details about the CRC_A field, please consult Appendix B of ISO/IEC 14443-3:2011 [45].

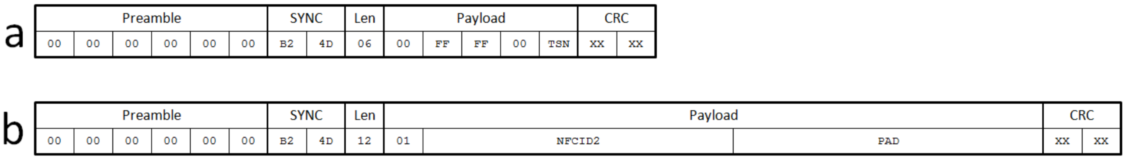


Figure 2.13: Anti-collision frame format for passive $^{f_c}/_{64}$ and $^{f_c}/_{64}$ devices. a) The SENS_REQ Polling Request frame sent by the Initiator during device detection. b) The SENS_RES Polling Response frame sent by the Target(s) during device detection [27]

.

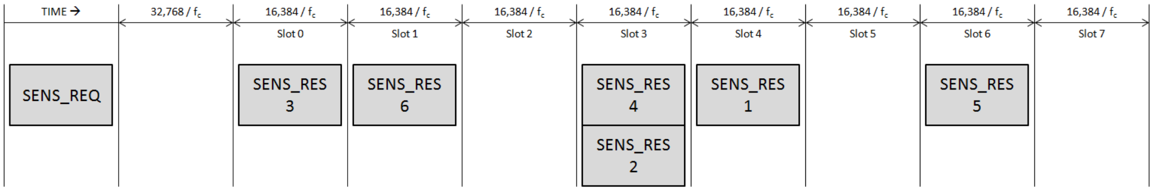
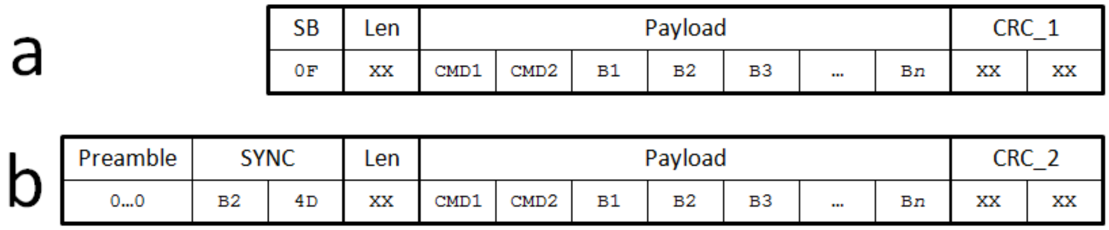


Figure 2.14: Example of the anti-collision algorithm for NFC-F devices. In this Figure, the Initiator can recognize Target devices 1, 3, 5, and 6, but not Target devices 2 and 4. Since there was a collision in time slot 3, the Initiator will repeat the SENS_REQ frame until it can detect the missing devices [27][46].

shows this process. The Initiator can recognize any device that uniquely responds in a time slot. When more than one Target device responds in the same time slot, a collision occurs and the Initiator cannot recognize those devices. When this happens, the Initiator repeats the process until all it has discovered all devices in range.

2.3.2.2 Data Exchange Protocol

Once single-device detection and anti-collision algorithms are complete, the Initiator can begin the Data Exchange Protocol (DEP). This protocol allows applications running on two NFC devices to communicate. There are three primary phases to the DEP. Figure 2.16 outlines the activation, data exchange, and deactivation phases for NFC devices using the passive communication mode and Figure 2.17 does the same for active devices. The process is largely the same in both communication modes. Once the Initiator has completed the single-device detection algorithm, it exchanges attributes with the Target (and possibly alters some of them) before moving into the DEP. Once communication is finished, the



a

SB	Len	Payload							CRC_1	
0F	XX	CMD1	CMD2	B1	B2	B3	...	Bn	XX	XX

b

Preamble	SYNC		Len	Payload							CRC_2	
0...0	B2	4D	XX	CMD1	CMD2	B1	B2	B3	...	Bn	XX	XX

Figure 2.15: a) Frame format for the Data Exchange Protocol (DEP) at a bit rate of ${}^{f_c}/_{128}$. b) Frame format for the DEP at bit rates of ${}^{f_c}/_{64}$ and ${}^{f_c}/_{32}$.

Initiator can deselect the Target and begin communicating with another Target or it can release all Targets and begin the process again.

For the DEP, all commands and responses use the same frame format, though this format varies slightly with the bit rate. Figure 2.15 shows the format of the DEP frame. Note that only the starting bytes differ with bit rate. The length field (Len) is always set to the number of bytes in the payload field plus one and has values in the range 3–255. The CMD1 and CMD2 bytes are always required. Some commands have additional required arguments. Finally, the CRC_1 is calculated according to appendix A.1 of the NFCIP-1 standard and CRC_2 is calculated according to appendix A.3 of the same [27].

Protocol Activation — The first step in the protocol activation phase is the attribute request (ATR_REQ). Figure 2.18 shows the formats of the ATR_REQ command and its paired ATR_REQ response. The ATR_REQ command establishes another unique device identification number (NFCID3i for active mode and ${}^{f_c}/_{128}$ passive mode, NFCID2t for others) that is valid until the Initiator releases the Target in the deactivation phase. If the Initiator has selected more then one target for data exchange, then it can use the DIDi field to specify which target a command is meant for, up to a maximum of 14 Target devices. The BSi and BRi fields indicate which data rates the Initiator supports (BSi for sending data, BRi for receiving data). The PPi field, also shown in Figure 2.18, has options for NFC-SEC (a cryptographic protocol, see Section 3.4), packet length reduction, and NAD, which provides packet routing for the application layer, similar to the way that sockets work in a typical TCP/IP stack. If there are other proprietary settings, then the ATR_REQ allows

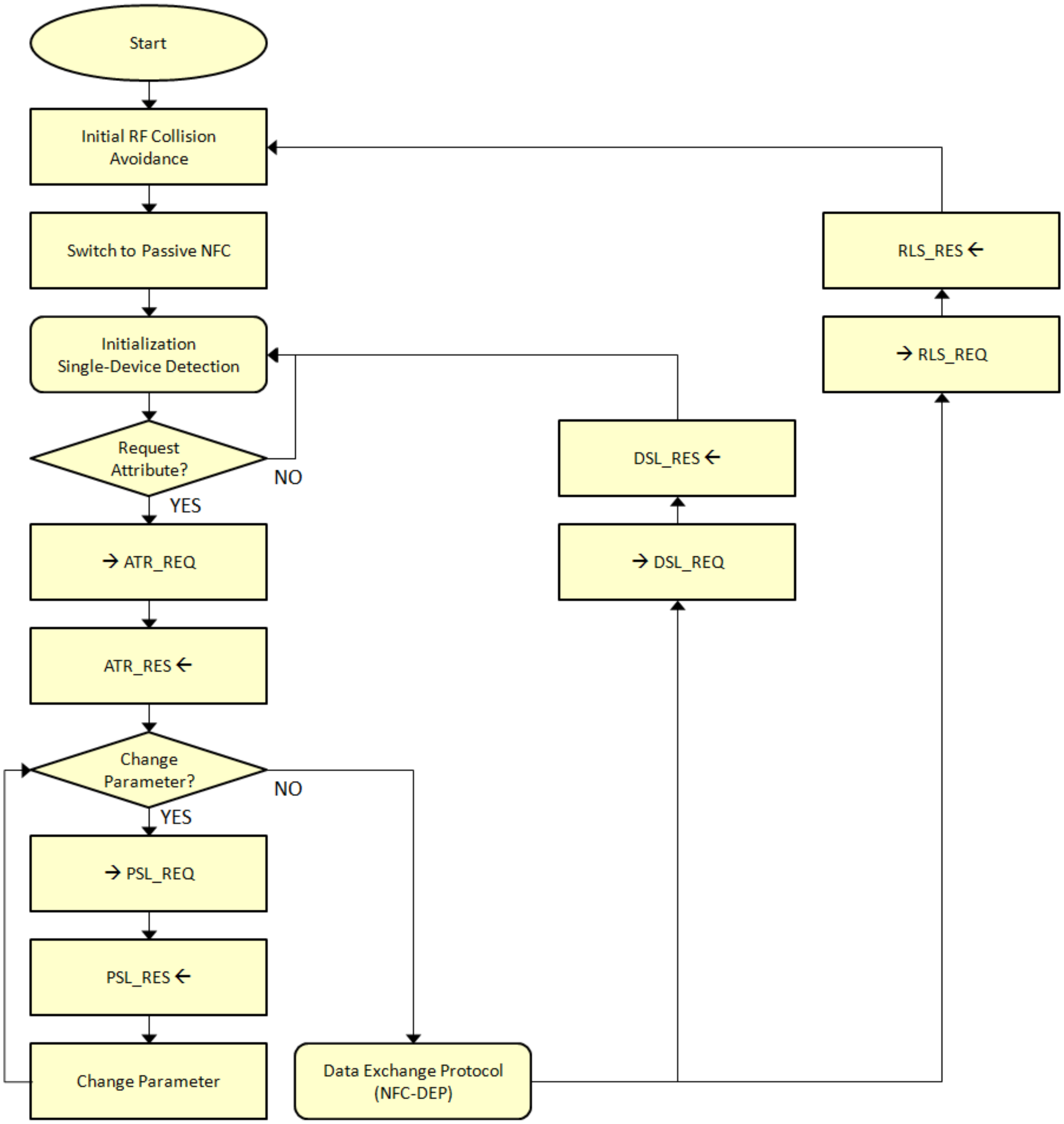


Figure 2.16: Flowchart of the Data Exchange Protocol for passive communication. If a Target does not support the ATR_REQ command, then it is not NFCIP-1 compliant and thus NFC-DEP is not possible [27][46].

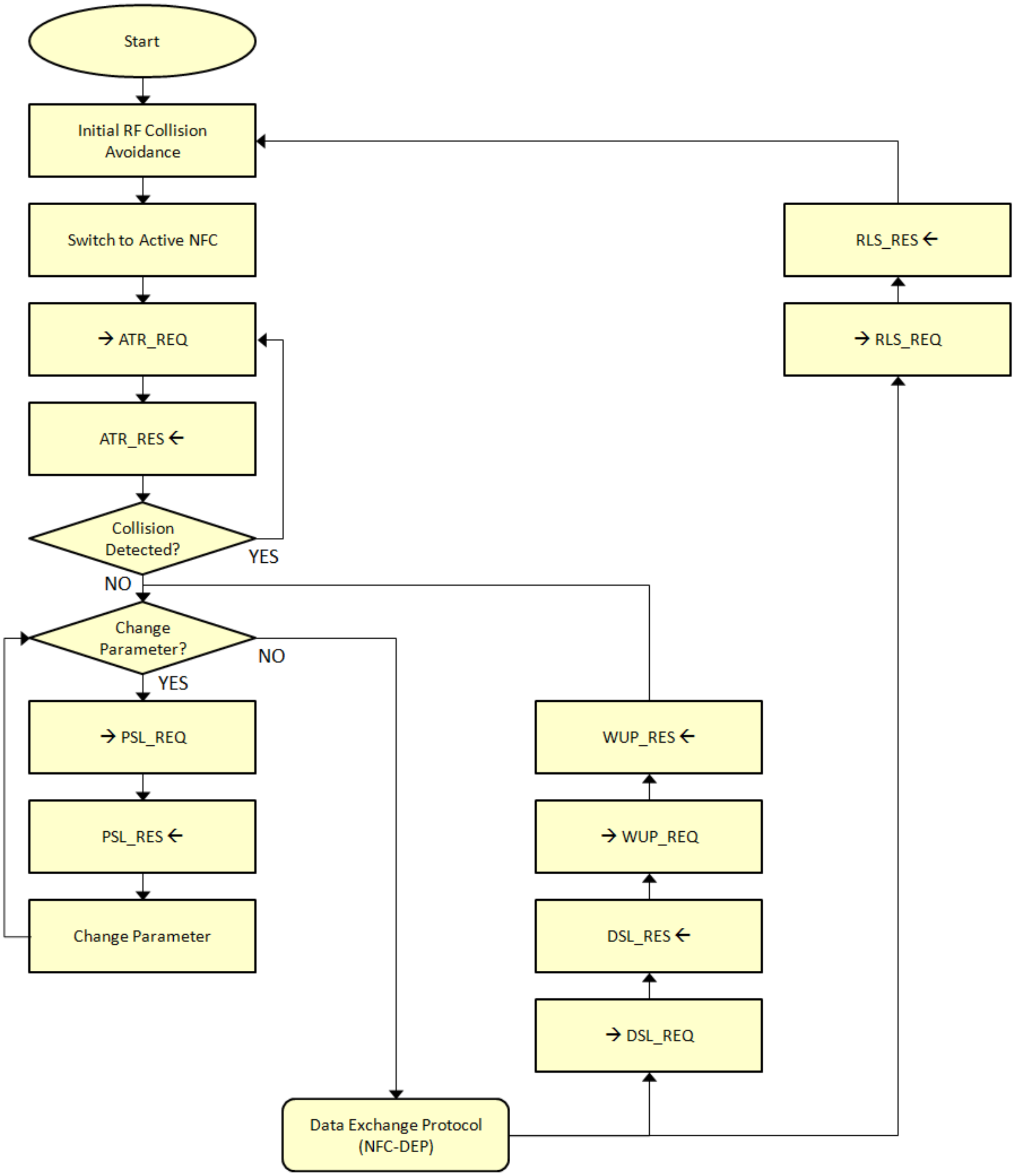
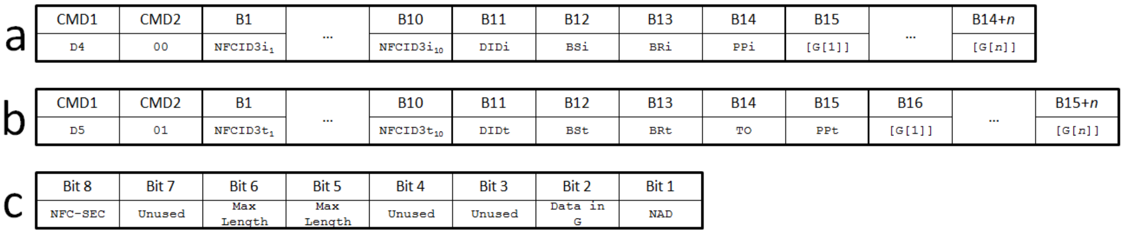


Figure 2.17: Flowchart of the Data Exchange Protocol for active communication. Recall that the ATR_REQ/ATR_RES sequence is the anti-collision protocol for active communication. In the active mode, deselected devices must be reactivated with a wakeup request (WUP_REQ) before the Initiator can communicate with them again [27][46].



CMD1	CMD2	B1	...	B10	B11	B12	B13	B14	B15	...	B14+n
D4	00	NFCID3i_1		NFCID3i_{10}	DIDi	BSi	BRi	PPi	[G[1]]		[G[n]]

CMD1	CMD2	B1	...	B10	B11	B12	B13	B14	B15	B16	...	B15+n
D5	01	NFCID3t_1		NFCID3t_{10}	DIDt	BSt	BRt	TO	PPt	[G[1]]		[G[n]]

Bit 8	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1
NFC-SEC	Unused	Max Length	Max Length	Unused	Unused	Data in G	NAD

Figure 2.18: a) Format of the ATR_REQ command. The bytes G(i) are optional and allow the devices to specify additional, non-standard information. b) Format of the ATR_RES response. C) Format of the PPi field.

additional bytes of data, though the total payload cannot exceed 255 bytes. The ATR_RES response is very similar to the ATR_REQ command, though it provides an additional field to specify a timeout value (TO).

Other commands used in the activation phase include the parameter select request (PSL_REQ) and its paired response (PSL_RES) and the wakeup request (WUP_REQ) and its paired response (WUP_RES). The PSL_REQ allows the Initiator to specify the Initiator-to-Target bit rate, the Target-to-Initiator bit rate, and the maximum frame length for future DEP communication. The WUP_REQ allows the Initiator to wake an active-mode Target from the sleep state [27].

Data Exchange — The only two commands used for data exchange are the Data Exchange Protocol (DEP) Request (DEP_REQ) and DEP Response (DEP_RES). These two commands share the same payload format, which is shown in Figure 2.19. The DID and NAD fields are the same as those used in the activation phase. The PFB field determines the type of each data frame. There are four possible options:

1. ”000” is an Information PDU (primary data unit), which contains information used by the application layer,

2. ”001” is a Protected PDU, which is a PDU using the NFC-SEC protocol (see Section 3.4),

3. ”010” is an ACK/NACK PDU, which acknowledges the last DEP frame,

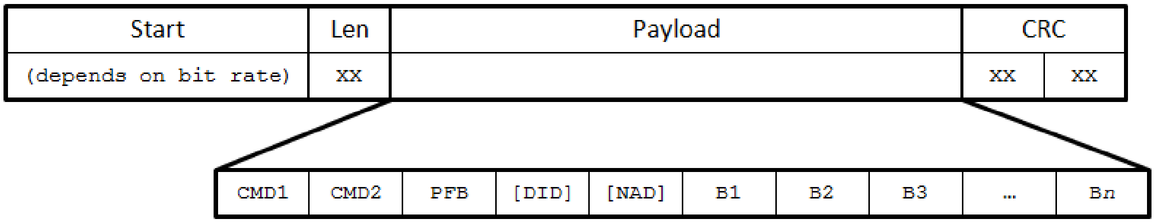


Figure 2.19: Payload of a DEP frame. The start and CRC fields depends on which bit rate is in use, as described in the text.

4. ”100” is a Supervisory PDU, which comes in two flavors:

   (a) Attention, which allows the Initiator to check that a Target is still present,

   (b) Timeout Extension, which asks the Initiator for more time to complete a command.

In addition, the PFB field can specify that that Multiple Information data chaining feature is active, which indicates to the receiving device that the incoming data is contained in more than one frame. When using this feature, each frame requires an ACK before the next frame can be sent.

Protocol Deactivation — To deactivate a Target, the Initiator has two options. First, it can use the deselect request (DSL_REQ, DSL_RES). This command releases the device ID (DID) that the Initiator had assigned for the Target. To reactivate a Target after using this command, the Initiator must issue a WUP_REQ in active mode or begin the single-device detection algorithm in passive mode. In both cases, the Target received a new DID.

Alternatively, the Initiator can issue the release request (RLS_REQ, RLS_RES), which instructs Targets to return to their initial state. To communicate with a Target after issuing this command, the Initiator must begin with the Initial RF Collision Avoidance algorithm and proceed through the single-device detection and protocol activation phases.

2.3.3 Logical Link Control

The NFCIP-1 standard specified the operating of NFC devices through the analog and digital interfaces. Indeed, the NFCIP-1 specification is all that one needs to create NFC-compliant devices. However, the NFC Forum maintains its own collection of NFC standards that further clarify and expand the ISO/IEC standards. Some of these standards clarify existing ISO/IEC standards, such as ANALOG [36], DIGITAL [44], and ACTIVITY [46]. Others add new functionality on top of the underlying NFCIP-1 specifications. The next layer in the stack is the Logical Link Control Protocol (LLCP), which is specified by the LLCP standard from the NFC Forum [37]. This layer is approximately equivalent to the top half of the OSI model's Data Link Layer (see Figure 2.3).

The LLCP simplifies the transfer of data from one NFC device to another by providing a uniform interface to higher layers in the stack. Among the features that the LLCP provides are link activation, supervision, and deactivation, aggregation and disaggregation of smaller digital-layer frames, and a "synchronous balanced transfer mode", which allows Target devices to initiate communication and manage connections. This last feature contrasts with vanilla NFCIP-1, which reserves these operations for Initiator devices. Figure 2.20 shows the structure of the primary components of the LLC layer.

Connection-oriented transport provides services similar to the Transmission Control Protocol (TCP) from the Internet Protocol suite. Before exchanging data, two devices using the connection-oriented transport feature first establish a data link connection. Then, each information packet sent by one device is acknowledged by the receiving device once it has passed that information up to the application layer. Devices maintain a sliding window of sent, unacknowledged packets (PDUs) that can vary in size with a maximum of 15 unacknowledged PDUs. This transport mode guarantees sequential delivery of information.

In contrast, connection-less transport provides very few features. Similar to the User Datagram Protocol (UDP) from the Internet Protocol Suite, connection-less transport does not guarantee delivery of information. There is no established link between devices and PDUs are not acknowledged. While the NFCIP-1 protocols guarantee that PDUs will reach the intended device, the connection-less transport mode does not guarantee that they will reach the intended application.

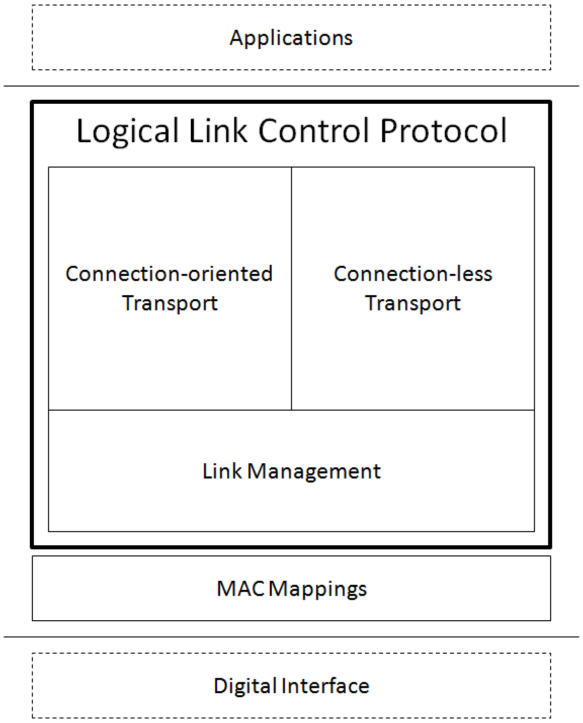

Applications
Logical Link Control Protocol
Connection-oriented Transport
Connection-less Transport
Link Management
MAC Mappings
Digital Interface

Figure 2.20: Structure of the LLC layer. The MAC mapping sublayer allows the LLC to interface with various other digital interfaces, but this text only considers those NFC devices using the NFC-DEP protocol [37].

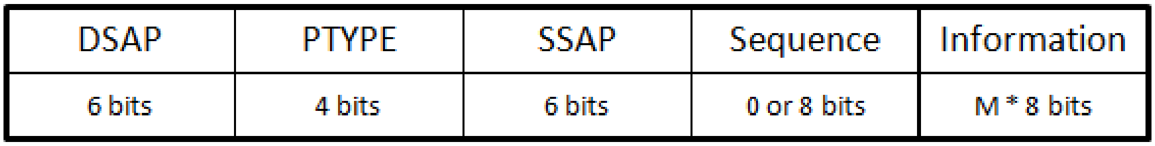
2.3.3.1 LLCP Frames

All LLCP PDUs use the same frame format, which is illustrated in Figure 2.21. The Destination Service Access Point (DSAP) field identifies which service on the receiving device the PDU is intended for. Similarly, the Source SAP (SSAP) field maps to the service that generated the PDU on the sending device. Addresses come in three flavors, according to Table 2.4 [37][47].

The PDU Type (PTYPE) field specifies the type of PDU. Some notable PTYPEs are CONNECT ("0100") for establishing connection-oriented transport links, I ("1100") for Information PDUs, and DISCONNECT ("0101") for disconnecting connection-oriented transport links. Some LLCP PDUs require a sequence number (*e.g.*, Information PDUs), while others do not (*e.g.*, CONNECT, DISCONNECT). Finally, the Information field contains any additional parameters or data. The maximum length of this field is 128 bytes, though

Table 2.4: Service Access Point Address Mapping for LLCP.

SAP	Description
00h–0Fh	Well-Known Service Access Points
00h	· · · LLCP Link Management
01h	· · · Service Discovery Protocol (SDP)
04h	· · · Simple NDEF Exchange Protocol (SNEP)
10h–1Fh	Services in the local service environment that are advertised by SDP
20h–3Fh	Services in the local service environment that are not advertised by SDP



DSAP	PTYPE	SSAP	Sequence	Information
6 bits	4 bits	6 bits	0 or 8 bits	M * 8 bits

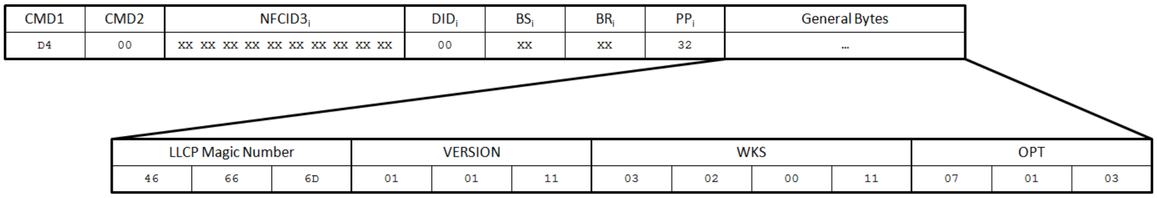
Figure 2.21: Format of the LLCP PDU. The value of M is 0–128 by default, though devices can specify a larger maximum upon link establishment. Not all PDUs have the Sequence field [37].

devices can establish a higher maximum when establishing a link.

2.3.3.2 MAC Mapping

The LLC layer can support different MAC mappings. However, the NFC Forum only specifies the NFC-DEP mapping. This mapping sits atop the Digital Interface described in Section 2.3.2, but with the following notable restrictions [37]:

- The Device ID (DID) feature is not used.
- The NAD feature is not used.
- Timeout Extension PDUs are not used.
- The Attention PDU is used only for exceptions.



CMD1	CMD2	NFCID3$_i$	DID$_i$	BS$_i$	BR$_i$	PP$_i$	General Bytes
D4	00	xx xx xx xx xx xx xx xx xx xx	00	xx	xx	32	...

LLCP Magic Number			VERSION			WKS				OPT		
46	66	6D	01	01	11	03	02	00	11	07	01	03

Figure 2.22: Example of an ATR_REQ that supports LLCP. This device uses version 1.1 of LLCP, keeps the default MIU of 128, supports the LLC Protocol and the Simple NDEF Exchange Protocol (see Section 2.3.4), keeps the default LTO of 100 ms, and supports both connection-oriented and connection-less transport modes.

- The payload length value for ATR_REQ and similar commands is always set to “11” for a maximum length of 255 bytes.

2.3.3.3 Activating a Link

In order to activate the LLC protocol, the MAC sets the first three General Bytes of ATR_REQ (G(1)–G(3)) to “46h 66h 6Dh”. Following this, the MAC writes a number of additional LLC-related parameters into the General Bytes field. Table 2.5 [37] describes the parameters, called TLVs (type, length, value), and Figure 2.22 shows an example ATR_REQ frame with support for LLCP. Only the VERSION TLV is mandatory and only the TLVs included in Table 2.5 are supported.

Once the Target device receives the LLCP-enabled ATR_REQ, it issues an ATR_RES with the same format for the General Bytes field. Then, both devices continue the normal NFC-DEP activation algorithm, including parameter selections. When both devices enter the DEP stage, they notify their local LLC layers that a connection is complete. At this point, the LLC layer takes over.

The LLC layers must agree on a protocol version number before proceeding. If the major and minor version numbers for both the ATR_REQ and the ATR_RES match, then the version number is that of the ATR_REQ. If the major numbers match, but the minors do not, then the version number is the lower of the two. If the major numbers do not match, then the device with the higher major number determines if the other device’s version number is compatible. If so, then both devices use the lower version number. If not, then the link activation fails.

Table 2.5: TLVs for NFC-DEP ATR_REQ frames.

Name	Type	Length	Value
VERSION	01h	01h	Bits 7–4 encode the major version number. Bits 3–0 encode the minor version number.
MIUX	02h	02h	The Maximum Information Unit Extension specifies the maximum length of the Information field of a LLCP PDU. $MIUX = MIU - 128$
WKS	03h	02h	The Well-Known Service parameter encodes which well-known services this device is configured to use. The lsb is always ‘1’ since this device supports the LLC Protocol.
LTO	04h	01h	Link Time-Out specifies the maximum time between the last bit received by a device and the first bit transmitted in response.
OPT	07h	01h	Bit 1 is set if the device supports connection-oriented transport. Bit 0 is set if the device supports connection-less transport.

Once the version number is agreed to, the devices determine the maximum length of the Information field of LLCP PDUs. If a device did not specify the MIUX TLV in the ATR_REQ or ATR_RES, then the default of 128 bytes is used. Otherwise, each device uses the value that it received in MIUX + 128. Each device has its own MIU and they do not need to be equal. A transmitting device never violates the receiving device’s MIU, regardless of its own MIU value.

2.3.3.4 Exchanging Data

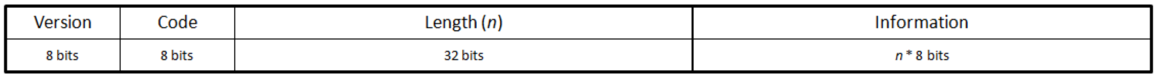
With the link established, the two devices can begin to exchange application data. In this phase, the Initiator sends DEP_REQ frames to the Target and the Target sends

DEP_RES frames to the Initiator. When a LLCP PDU does not fit into a single DEP frame, the Multiple Information chaining mechanism described in Section 2.3.2.2 is used. When receiving chained data, the MAC reassembles it into a single LLCP PDU before passing it up to the LLC layer. During the date exchange phase, either the connection-less transport mode or the connection-oriented transport mode can be used.

Connection-less Transport — The connection-less transport mode does not require the establishment of a data link and thus also does not require the disconnection of such a link. In this mode, all information is sent with the Unnumbered Information (UI) PDU, which does not use a sequence number. Both devices are able to send and received UI PDUs at any time, within the limits of the NFC-DEP protocol, and neither device ever acknowledges receipt of a UI PDU from the other device. Both devices are free to ignore incoming PDUs for any reason.

Connection-oriented Transport — In contrast to connection-less mode, the connection-oriented transport mode does require establishing a logical data link before exchanging other data. A device can request to establish a data link with the CONNECT PDU, which specifies the MIUX to use for the connection, the receive window size, and the name of the service on the remote device to which the local device wishes to establish a data link. The remote device responds with a Connection Complete (CC) PDU, which specifies the MIUX and receive window size for the remove device.

With the data link established, the two devices can now exchange data using Information (I) PDUs. These PDUs use a sequence number to ensure that the receiving device receives them in the correct order. Each I PDU must be acknowledged by the receiving device with a Receive Ready (RR) PDU. If the receiver is not ready for the next I PDU, it instead sends the Receive Not Ready (RNR) PDU. When it later becomes ready, it then sends the RR PDU. If there is a problem with a received I PDU, then the receiver can reply with a Frame Reject (FRMR) PDU to inform the sending device of the problem and the sending device can choose to resend the errored frame. Using this protocol, both devices can be sure that each frame is sent and received in the proper order and without error.



Version	Code	Length (*n*)	Information
8 bits	8 bits	32 bits	*n* * 8 bits

Figure 2.23: Simple NDEF Exchange Protocol (SNEP) frame format. The upper nibble of Version encode the major version number while the lower nibble encodes the minor version number. The Code is a request code for frames sent by a SNEP client and a response code for frames send by a SNEP server. Not all frames have the Information field [48].

When a device wishes to terminate a data link, it sends the Disconnect (DISC) PDU with the DSAP field populated with the access point of the service to disconnect from. In response, the remote device informs the application-layer service of the disconnection and then issues the Disconnect Mode (DM) PDU to confirm the data link disconnection.

2.3.3.5 Deactivating a Link

To terminate the LLC link connection, a device issues the DISC PDU with the DSAP set to 00h to indicate the LLCP service. The other device responds with the DM PDU. Once this is complete, the LLC layers inform their respective MAC layers to disconnect. The Initiator sends the DSL_REQ frame, which the Target answers with the DSL_RES frame. This completes both the NFC-DEP and LLC protocols.

2.3.4 Simple NDEF Exchange Protocol

The Simple NDEF Exchange Protocol (SNEP), defined by the NFC Forum's SNEP specification [48] sits atop the LLC layer and acts as a service that allows two NFC Forum devices to exchange NFC Data Exchange Format (NDEF) messages (see Section 2.3.5). The SNEP service is found at SAP 04h [47]. SNEP frames are transmitted in the Information field of LLCP PDUs and have the format shown in Figure 2.23. The largest NDEF message that can fit into a SNEP frame is $2^{32} - 1$ bytes because this is the largest value that fits into the 32-bit Length field.

When a SNEP message does not fit into a single LLCP PDU, it is split into multiple PDUs. Upon receiving the first PDU, the receiving device checks the protocol version number of the received frame using an algorithm similar to the one used by the LLC Protocol. If the received protocol version is supported, then the receiving device can send

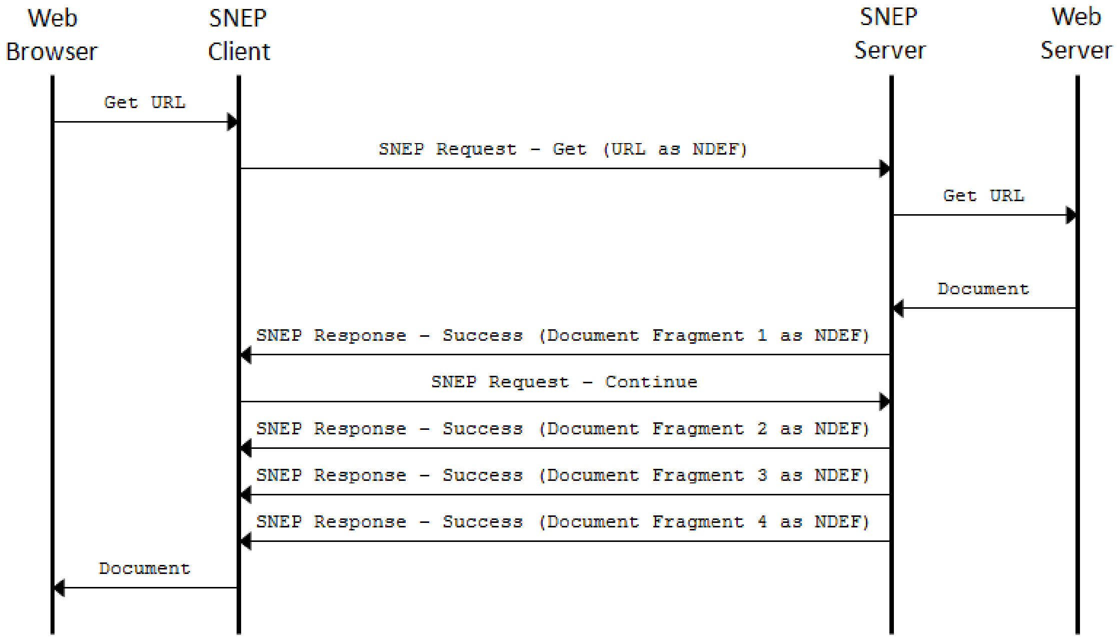

Web Browser
SNEP Client
SNEP Server
Web Server
Get URL
SNEP Request - Get (URL as NDEF)
Get URL
Document
SNEP Response - Success (Document Fragment 1 as NDEF)
SNEP Request - Continue
SNEP Response - Success (Document Fragment 2 as NDEF)
SNEP Response - Success (Document Fragment 3 as NDEF)
SNEP Response - Success (Document Fragment 4 as NDEF)
Document

Figure 2.24: Example of a fragmented SNEP message. The web server sends a URL encoded as a NDEF message to the SNEP client, which sends a "Get" request to the SNEP server. The SNEP server passes the URL to the web server, which retrieves the document and passes it to the SNEP server as a NDEF message. Since the document is too large to fit into one SNEP message, the SNEP server splits it into four fragments. Once the SNEP client has received all four fragments, it passes the NDEF document back to the web browser [48].

a "Continue" frame, which prompts the sending device to send the remaining pieces of the SNEP message. If the protocol version is not supported, then the receiving device sends a "Unsupported Version" frame and the transaction is complete. Figure 2.24 illustrates an example in which the SNEP client requests a message from a SNEP server and the SNEP server's response does not fit into a single SNEP frame.

There are four request codes that the SNEP client can send to a SNEP server, which are summarized in Table 2.6 [48]. The "Continue" request code asks the SNEP server to send the remaining fragments of a fragmented SNEP message. The Information field of a "Continue" request is empty and so the Length field is zero. If the client is unable or unwilling to receive the remaining fragments, then it instead sends a "Reject" request. This request also contains an empty Information field.

Table 2.6: SNEP request codes.

Code	Name	Info	Description
00h	Continue	NO	Tells the server to send remaining message fragments.
01h	Get	YES	Asks the server to send a NDEF message.
02h	Put	YES	Asks the server to accept a NDEF message.
7Fh	Reject	NO	Tells the server not to send remaining message fragments.

The “Get” request code asks the server to send a NDEF message. The Information field of a “Get” message contains a 32-bit field specifying the maximum length of the response message that the client can handle and then a single NDEF message specifying which message to retrieve. For instance, a web browser on the client device might send a URL as the NDEF message in a “Get” request and a an application running on the SNEP server device would then send the contents of the document located at that URL as an NDEF message in response. Finally, the client can send a “Put” request that asks the server to accept an NDEF message. The server can then pass this message up to the appropriate application.

Table 2.7 [48] summarizes the eight response codes that a SNEP server can send. Two of them, “Continue” and “Reject”, work just as they do for the SNEP client. The server can also send the “Success” code, which indicates that the “Get” or “Put” request was successful. In the case of a “Get”, the “Success” response contains the requested NDEF message. For “Put” requests, the “Success” response has no Information field.

The rest of the server’s response codes deal with error conditions. “Not Found” indicates that the server could not find the requested NDEF message, “Excess Data” indicates that the server has found the requested message, but that it is too large to send to the client, “Bad Request” indicates that the server could not understand the request (possibly because it was malformed), “Not Implemented” means that the server cannot fulfill the request because it does not support the required functionality, and “Unsupported Version” means that the

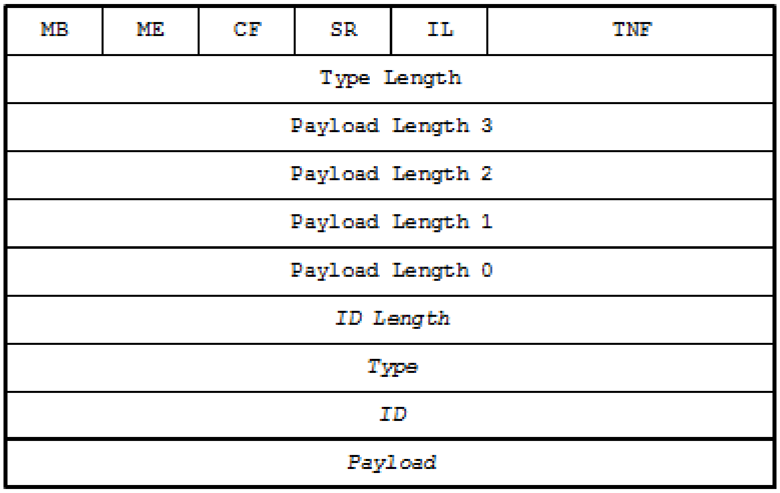
Table 2.7: SNEP response codes.

Code	Name	Info	Description
80h	Continue	NO	Tells the client to send remaining message fragments.
81h	Success	YES	Informs the client of a successful Get or Put operation.
C0h	Not Found	NO	Informs the client that the requested NDEF message was not found.
C1h	Excess Data	NO	Informs the client that the requested NDEF message is too large.
C2h	Bad Request	NO	Informs the client that the server could not understand the request.
E0h	Not Implemented	NO	Informs the client that the server cannot fulfill the request.
E1h	Unsupported Version	NO	Informs the client that the server does not support its protocol version.
FF	Reject	NO	Tells the client not to send remaining message fragments.

server does not support the SNEP version that the client is using. None of these error code frames have an Information field.

2.3.5 NFC Data Exchange Format

The NFC Data Exchange Format (NDEF) message and record are specified by the NFC Forum's NDEF specification [49]. The goal of NDEF is to provide NFC devices with a simple, uniform way to exchange data of any type. A NDEF message is one or more NDEF records. While one NDEF message cannot contain another NDEF message, a NDEF message can contain a NDEF record which itself contains a full NDEF message. Thus, NDEF messages can be nested. There is no limit to the number of NDEF records contained in a NDEF message.



MB	ME	CF	SR	IL	TNF
Type Length					
Payload Length 3					
Payload Length 2					
Payload Length 1					
Payload Length 0					
ID Length					
Type					
ID					
Payload					

Figure 2.25: Format of an NDEF record. The fields with italicized labels have variable lengths. The size of the Type, ID, and Payload fields are encoded in the Type Length, Payload Length, and ID Length fields, respectively. If the IL flag is not set, then neither the ID Length field nor the ID field is included in the record. If the Type Length or Payload Length is zero, then the respective Type or Payload field is not present in the record [49].

Figure 2.25 show the format of a NDEF record. The Message Begin (MB) flag is set for the first NDEF record in a NDEF message and the Message End (ME) flag is set for the final NDEF record in a NDEF message. If the message has only one record, then both flags are set. The Chunk Flag (CF) flag indicates that a record is either the first chunk or an intermediate chunk of a chunked payload. The final chunk of a chunked payload does not set CF. The Short Record (SR) flag indicates that this NDEF record is of the short record format (see Figure 2.26). Finally, the ID Length (IL) flag is set when the ID Length field is present in the record. The Type Name Format (TNF) field encodes the format of the Type field.

The maximum length of the payload in a normal NDEF record is $2^{32} - 1$ bytes because the Payload Length field is 32 bits. Longer application payloads can be separated into chunks using the chunked payload feature. The full payload must be contained in a single NDEF message, which has no limit on size. Chunked payloads have an initial record, zero or more intermediate records, and a final record. The initial record of a chunked payload also specifies the payload type and (optionally) the ID for the entire set. Subsequent records set

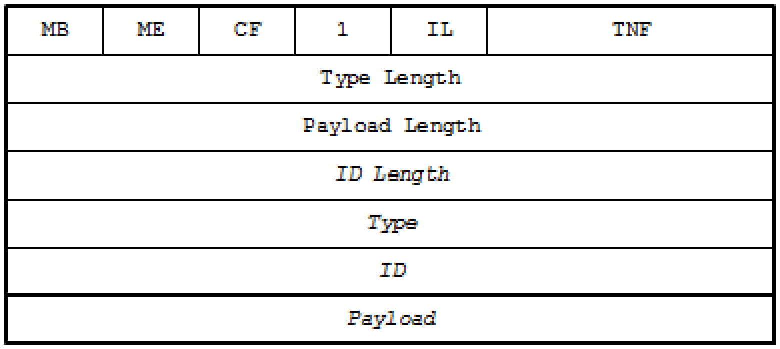


Figure 2.26: Format of an NDEF short record. Short records have a maximum payload size of 255 bytes, but are otherwise identical to normal NDEF records [49].

the TNF field to 06h (unchanged), set the IL flag to ‘0’, set the Type Length field to zero, and omit the Type, ID Length, and ID fields entirely. Each record in the chunked payload sets its Payload Length flag to the length of the Payload field for that specific record and not for the overall payload.

There are no restrictions on what the NDEF payload contains. However, the NDEF record does provide a system for helping an NFC device determine to which application it should send an incoming NDEF message and from which application such a message was generated. Table 2.8 [49] summarizes the possible encodings for the Type field. The contents of the Type field determine the specific type of the payload. For instance, a JPEG image would have a TNF of 02h (MIME) and a Type of “image/jpeg”.

2.4 Chapter Summary

Near Field Communication (NFC) devices build upon the ideas of Radio Frequency Identification (RFID). NFC devices communicate with passive devices and tags, including a subset of RFID devices, and also communicate with other active devices. Regardless of the mode of operation, NFC devices use a multi-layered communication model similar to the Internet Protocol Suite or the ISO Model. The NFC Forum expands on the NFC standards with additional layers, including the NFC Data Exchange Format, which provides a simple, universal way to exchange information with NFC devices and tags.

Table 2.8: TNF encoding for NDEF records.

Value	Type Name Format
00h	Empty (no payload)
01h	NFC Forum Well-Known Type [50]
02h	Media Type (MIME) [51]
03h	Absolute URI [52]
04h	NFC Forum External Type [50]
05h	Unknown
06h	Unchanged (for chunked payloads)

Chapter 3

Cryptography Overview

The ECMA-385 [53] standard describes the NFC Security and Services Protocol (NFC-SEC) and ECMA-386 [54] describes a means of implementing that protocol. This chapter describes NFC-SEC and the cryptographic algorithms used to implement it.

3.1 Advanced Encryption Standard

The Advanced Encryption Standard (AES) is a method for encrypting electronic data. In 2001, the National Institute of Standards and Technology (NIST) announced AES as Federal Information Processing Standards Publication 197 [56]. Since then, AES has been adopted by the United States government as a replacement for the Data Encryption Standard (DES), and the National Security Agency approved the use of AES for encrypting SECRET and TOP SECRET classified information [57]. Many modern computer processors have special instructions for quickly encrypting data with AES [58] and many software libraries take advantage of these special instructions, including the popular OpenSSL security suite [59]. In summary, AES is a powerful, widely-used encryption algorithm.

The input to AES is a message, called the `plaintext`, and the output is an encrypted message, called the `ciphertext`. At a high level, AES uses a secret number, called the `cipher key`, to perform mathematical operations on the bits that make up the plaintext. AES supports key sizes or 128, 192, and 256 bits. The NFC-SEC protocol uses a key size of

Parts of this Chapter were submitted for publication to Elsevier Computer Communications [55].

Algorithm 3.1: Pseudo code of the AES algorithm.

```
AES(uint8 in[16], uint8 out[16], uint32 key[44]) {
    uint8 state[4][4] = in;      // state is in column major order!

    AddRoundKey(state, key[3:0]);

    for (round = 1; round < 10-1; round += 1) {
        SubBytes(state);
        ShiftRows(state);
        MixColumns(state);
        AddRoundKey(state, key[(round+1)*4-1:round*4]);
    }

    SubBytes(state);
    ShiftRows(state);
    AddRoundKey(state, key[43:40]);

    out = state;
}
```

128 bits, so this text focuses on the operation of AES with a key of that size. The plaintext input must be 128 bits, so longer messages are first subdivided into 128-bit chunks, or `blocks`. Then, the AES algorithm is run on each block to produce a 128-bit cipher of that block. Finally, the cipher blocks are concatenated together to form the final ciphertext. Algorithm 3.1 contains a pseudo-code implementation of the AES encryption algorithm for a 128-bit block size with a 128-bit cipher key. This Algorithm makes clear that the AES algorithm performs ten `rounds` of transformations on the plaintext to generate the ciphertext. The rounds are identical, except that the last round omits the `MixColumns` transformation. The functions `AddRoundKey`, `SubBytes`, `ShiftRows`, and `MixColumns` are explained later in the text.

For the remainder of this text, an 8-bit value is referred to as a `byte` and a 32-bit value is referred to as a `word`. Also, note that the `state` variable uses column major order. Thus, the plaintext bytes are arranged as follows:

$$\begin{bmatrix} b15 & b11 & b7 & b3 \\ b14 & b10 & b6 & b2 \\ b13 & b9 & b5 & b1 \\ b12 & b8 & b4 & b0 \end{bmatrix}$$

3.1.1 Finite Field Math

All bytes in the AES algorithm, including the initial `state`, are elements of a characteristic 2 finite field with 256 elements, or GF(2^8). For example, the binary value "11001010" is equivalent to "$x^7 + x^6 + x^3 + x$". In this field, addition and subtraction operations are equivalent to exclusive-OR operations ($\oplus$). Multiplication operations ($\bullet$) are more complicated (see Appendix A for an example of an algorithm) and are always performed modulo the irreducible polynomial, $m(x) = x^8 + x^4 + x^3 + x + 1$, represented in binary notation as "100011011". Two numbers in the field are multiplicative inverses if their product modulo $m(x)$ is 1. For example, the values 57h and 83h are multiplicative inverses [56], where:

$$(x^6 + x^4 + x^2 + x + 1) \bullet (x^7 + x + 1) \mod x^8 + x^4 + x^3 + x + 1 = 1.$$

Four-term polynomials with coefficients that are themselves finite field elements (*i.e.*, bytes rather than bits) behave differently than those just described. For instance, consider the following two polynomials:

$$a(x) = a_3x^3 + a_2x^2 + a_1x + a_0$$
$$b(x) = b_3x^3 + b_2x^2 + b_1x + b_0$$

where to add these values, we perform exclusive-OR operations on the coefficients, yielding:

$$a(x) + b(x) = (a_3 \oplus b_3)x^3 + (a_2 \oplus b_2)x^2 + (a_1 \oplus b_1)x + (a_0 \oplus b_0).$$

Multiplication is again more complex. First, we algebraically expand the polynomial product and, remembering that addition is equivalent to exclusive-OR, combines like terms. Thus, we obtain the following:

$$c(x) = a(x) \bullet b(x) = c_6x^6 + c_5x^5 + c_4x^4 + c_3x^3 + c_2x^2 + c_1x + c_0$$

$$c_0 = a_0 \bullet b_0 \qquad c_4 = (a_3 \bullet b_1) \oplus (a_2 \bullet b_2) \oplus (a_1 \bullet b_3)$$

$$c_1 = (a_1 \bullet b_0) \oplus (a_0 \bullet b_1) \qquad c_5 = (a_3 \bullet b_2) \oplus (a_2 \bullet b_3)$$

$$c_2 = (a_2 \bullet b_0) \oplus (a_1 \bullet b_1) \oplus (a_0 \bullet b_2) \qquad c_6 = a_3 \bullet b_3$$

$$c_3 = (a_3 \bullet b_0) \oplus (a_2 \bullet b_1) \oplus (a_1 \bullet b_2) \oplus (a_0 \bullet b_3).$$

As with all multiplication, multiplication with four-term coefficient polynomials is performed modulo another polynomial. For AES, this polynomial is "x^4+1", which will reduce $c(x)$ to a four-term polynomial (*i.e.*, a word).

Finally, the modular product of two polynomials $a(x)$ and $b(x)$ modulo x^4+1 is computed as follows:

$$a(x) \otimes b(x) = d(x) = d_3x^3 + d_2x^2 + d_1x + d_0$$

$$d_0 = (a_0 \bullet b_0) \oplus (a_3 \bullet b_1) \oplus (a_2 \bullet b_2) \oplus (a_1 \bullet b_3)$$

$$d_1 = (a_1 \bullet b_0) \oplus (a_0 \bullet b_1) \oplus (a_3 \bullet b_2) \oplus (a_2 \bullet b_3)$$

$$d_2 = (a_2 \bullet b_0) \oplus (a_1 \bullet b_1) \oplus (a_0 \bullet b_2) \oplus (a_3 \bullet b_3)$$

$$d_3 = (a_3 \bullet b_0) \oplus (a_2 \bullet b_1) \oplus (a_1 \bullet b_2) \oplus (a_0 \bullet b_3).$$

3.1.2 Key Schedule

The third parameter to the AES function in Algorithm 3.1, `key`, is a 44-word (176-byte) value. This value is computed from the original 128-bit cipher key according to the AES key schedule. Algorithm 3.2 illustrates the algorithm used to produce this key schedule in pseudo code [56].

The first sixteen bytes of the expanded key are equal to the first sixteen bytes of the original cipher key. Each following word is equal to the exclusive-OR of the previous word and the word four prior. For each fourth word, an additional transformation is applied. Each four-word key produced by this key expansion is considered a `round key`. In total, there are eleven such keys.

The `SubWord` function applies the SubBytes function described in Section 3.1.4 to each byte in the word, substituting it for another value found in a pre-computed lookup table. `RotWord` rotates the bytes in a word one position left so that $\{a_3, a_2, a_1, a_0\}$ becomes $\{a_2, a_1, a_0, a_3\}$. Finally, the `Rcon(i)` function computes the value $x^{(i-1)}$ in GF(2^8) using

Algorithm 3.2: Pseudo code of the AES key expansion.

```
KeyExpansion(uint8 cKey[16], uint32 eKey[44]) {
    uint32 temp;
    for (i = 1; i < 4; i += 1) {
        eKey[i] = cKey[4*i+3], cKey[4*i+2], cKey[4*i+1], cKey[4*i];
    }
    for (i = 4; i < 44; i += 1) {
        temp = eKey[i-1];
        if (i mod 4 == 0) {
            temp = SubWord(RotWord(temp));
            temp[3] = temp[3] xor Rcon(i/4);
        }
        eKey[i] = eKey[i-4] xor temp;
    }
}
```

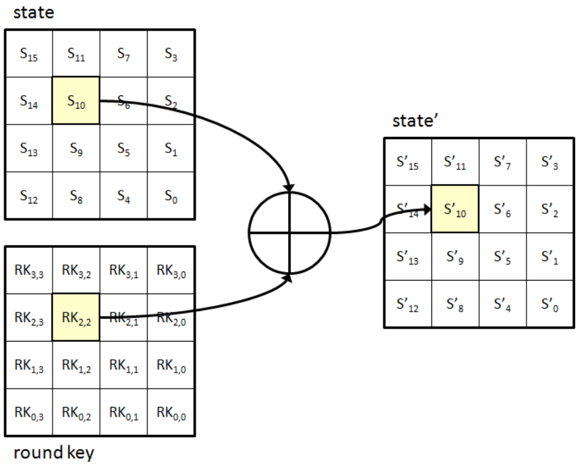
the rules described in Section 3.1.1. For example, to compute `Rcon(9)`, we perform the following computation:

$$\mathit{Rcon}(9) = x^{(9-1)} = x^8 \mod x^8 + x^4 + x^3 + x + 1 = x^4 + x^3 + x + 1 = \text{1Bh}.$$

In practice, the results of the `Rcon(i)` function are often precomputed and stored in a lookup table in order to increase the AES algorithm's performance.

3.1.3 AddRoundKey

The `AddRoundKey` function consumes the `state` and a round key and performs a bitwise exclusive-OR operation to produce the result. Figure 3.1 demonstrates this operation, where S is the state and RK is the round key. If the same cipher key is used to encrypt every block of plaintext, then every block will have the same key expansion. In a system with sufficient memory, the exclusive-OR operations can be replaced with 176 lookup tables, one for each byte in the expanded key. However, since modern processors include special instructions for AES and exclusive-OR operations are usually faster than memory lookups, this is rarely



S_{15}	S_{11}	S_7	S_3
S_{14}	S_{10}	S_6	S_2
S_{13}	S_9	S_5	S_1
S_{12}	S_8	S_4	S_0

S'_{15}	S'_{11}	S'_7	S'_3
S'_{14}	S'_{10}	S'_6	S'_2
S'_{13}	S'_9	S'_5	S'_1
S'_{12}	S'_8	S'_4	S'_0

$RK_{3,3}$	$RK_{3,2}$	$RK_{3,1}$	$RK_{3,0}$
$RK_{2,3}$	$RK_{2,2}$	$RK_{2,1}$	$RK_{2,0}$
$RK_{1,3}$	$RK_{1,2}$	$RK_{1,1}$	$RK_{1,0}$
$RK_{0,3}$	$RK_{0,2}$	$RK_{0,1}$	$RK_{0,0}$

Figure 3.1: Illustration of the AES `AddRoundKey` function. This operation is performed eleven times for each 128-bit block of plaintext [56].

done.

3.1.4 SubBytes

The `SubBytes` function performs a non-linear substitute of each byte in the `state`. In order to determine the new value of a byte, first find its multiplicative inverse in GF(2^8) according to the rules in Section 3.1.1. Then, for each bit in the byte, apply the following affine transformation over GF(2), where $c = 63$h and all subscripts are modulo 8:

$$b'_i = b_i \oplus b_{(i+4)} \oplus b_{(i+5)} \oplus b_{(i+6)} \oplus b_{(i+7)} \oplus c_i.$$

Alternatively, the affine transformation can be represented in array form. In this case, the modular multiplication and addition operations are performed over GF(2^8), yielding:

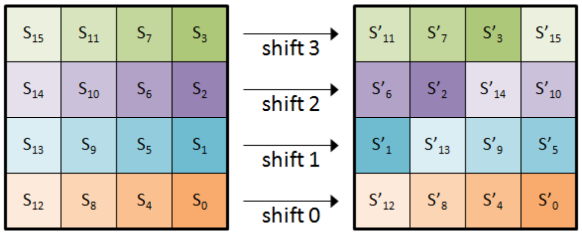


Figure 3.2: Illustration of the AES `ShiftRows` function. This operation is performed ten times for each 128-bit block of plaintext [56].

$$\begin{bmatrix} b'_0 \\ b'_1 \\ b'_2 \\ b'_3 \\ b'_4 \\ b'_5 \\ b'_6 \\ b'_7 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 0 \end{bmatrix} .$$

The results of transformation are often pre-computed and stored in a lookup table called the S-Box. When `SubWords` is called during the key expansion algorithm, it uses the same S-Box lookup table as `SubBytes`. SubBytes is performed on `state` ten times for each 128-bit block of plaintext.

3.1.5 ShiftRows

The `ShiftRows` function rotates the bytes in each row of `state`. The number of positions that each byte moves is equal to the row of that the byte resides in. As a result, bytes in row 0 are not shifted, bytes in row 1 are shifted one position, and so on. Figure 3.2 illustrates this function.

3.1.6 MixColumns

`MixColumns` operates on each column in `state`. Each column is a four-term polynomial over GF(2^8). Using the polynomial $a(x) = 3x^3 + 1x^2 + 1x + 2$, the result of `MixColumns` is

$s'(x) = a(x) \otimes s(x)$. Or, in matrix form, we get:

$$\begin{bmatrix} s'_{3,c} \\ s'_{2,c} \\ s'_{1,c} \\ s'_{0,c} \end{bmatrix} = \begin{bmatrix} 02h & 01h & 01h & 03h \\ 03h & 02h & 01h & 01h \\ 01h & 03h & 02h & 01h \\ 01h & 01h & 03h & 02h \end{bmatrix} \begin{bmatrix} s_{3,c} \\ s_{2,c} \\ s_{1,c} \\ s_{0,c} \end{bmatrix}.$$

As with other AES functions, the `MixColumns` is often pre-computed as a set of lookup tables to avoid doing multiplication on GF(2^8). This function is performed nine times for each 128-bit block of plaintext.

3.1.7 Decryption

Decryption of AES ciphertext is performed with the same cipher key and expanded key as encryption. The order of operations is changed, as illustrated in Algorithm 3.3.

Note that because `AddRoundKey` is simply an exclusive-OR operation, it is its own inverse function. However, the other three functions are modified in the following manner:

- `InvShiftRows` The bytes are rotated in the opposite direction. So, $\{S'_{11}, S'_7, S'_3, S'_{15}\}$ becomes $\{S_{15}, S_{11}, S_7, S_3\}$.
- `InvSubBytes` The substitution uses an inverse S-Box, which is obtained by applying the inverse of the transform described in Section 3.1.4 and then taking the multiplicative inverse of the results in GF(2^8).
- `InvMixColumns` The polynomial is $a^{-1}(x) = 11x^3 + 13x^2 + 9x + 15$.

As with the original algorithm functions, these functions are often pre-computed and stored as lookup tables to improve the efficiency of the inverse algorithm. Each inverse function is performed the same number of times as its original counterpart.

3.2 Diffie-Hellman

The Diffie-Hellman key exchange algorithm (DH), devised by Whitfield Diffie, Martin Hellman, and Ralph Merkle [60] was first published in 1976 [61] and it allows for two users

Algorithm 3.3: Pseudo code of the inverse AES algorithm.

```
AES_Inverse(uint8 in[16], uint8 out[16], uint32 key[44]) {
    uint8 state[4][4] = in;      // state is in column major order!

    AddRoundKey(state, key[3:0]);

    for (round = 10-1; round > 0; round -= 1) {
        InvShiftRows(state);
        InvSubBytes(state);
        AddRoundKey(state, key[(round+1)*4-1:round*4]);
        InvMixColumns(state);
    }

    InvShiftRows(state);
    InvSubBytes(state);
    AddRoundKey(state, key[43:40]);

    out = state;
}
```

to devise a `shared secret` that they can use to encrypt and decrypt messages. Since it does not require either party to have prior knowledge about the other, it can be used to establish a secure communication link over an insecure channel.

To begin, the two parties first exchange some public information. In the original implementation, this information was a pair of numbers, p and g such that p is prime and g is a primitive root of p. That is, for every integer a co-prime to p, there is an integer k such that $g^k \equiv a \mod n$. For example, consider $p = 5$. The integers co-prime to p are then 1, 2, 3, and 4. The integer $g = 2$ is is a primitive root of p because the values $k = \{4, 1, 3, 2\}$ satisfy the requirement, as follows:

$$\begin{aligned}
2^4 &= 16 &= 1 \mod 5\\
2^1 &= 2 &= 2 \mod 5\\
2^3 &= 8 &= 3 \mod 5\\
2^2 &= 4 &= 4 \mod 5.
\end{aligned}$$

All arithmetic is performed modulo p, forming a finite cyclic group with g as the generating element. Once the two parties agree on the initial parameters, the first party, Alice, chooses a random integer, a, and calculates $A = g^a \mod p$. Alice sends this new value, A, to the second party, Bob. Similarly, Bob chooses a random integer, b, and calculates $B = g^b \mod p$, which he sends to Alice. Finally, both parties compute the shared secret, s, using the following operations:

$$\begin{aligned}
&\text{Alice:} \qquad s = B^a \mod p\\
&\text{Bob:} \qquad s = A^b \mod p.
\end{aligned}$$

Note that the shared secret s is equal for both Alice and Bob because $(g^a)^b \mod p \equiv (g^b)^a \mod p$. When Alice wishes to send a message m to Bob, she multiplies the message by the shared secret and sends ms. To decrypt it, Bob calculates s^{-1} and then applies it to recover the received message, $m = mss^{-1}$. When Bob sends a message to Alice, the operations are reversed. Figure 3.3 shows a simple example of the DH key exchange algorithm.

In practice, the values for a, b, and p would need to be much larger. This is due to the fact that for large values, there is no efficient algorithm to recover a or b given only p, g, A, and B, a problem known as the discrete logarithm problem. In addition, while the original DH implementation used the same secret to encrypt and decrypt messages for both, modern implementations use a pair of encryption and decryption keys for each user to provide additional security. Finally, the public information does not need to be a pair of integers. Other finite cyclic groups work as well. NFC-SEC uses a popular variation of DH in which the public information are the parameters to an elliptic curve.

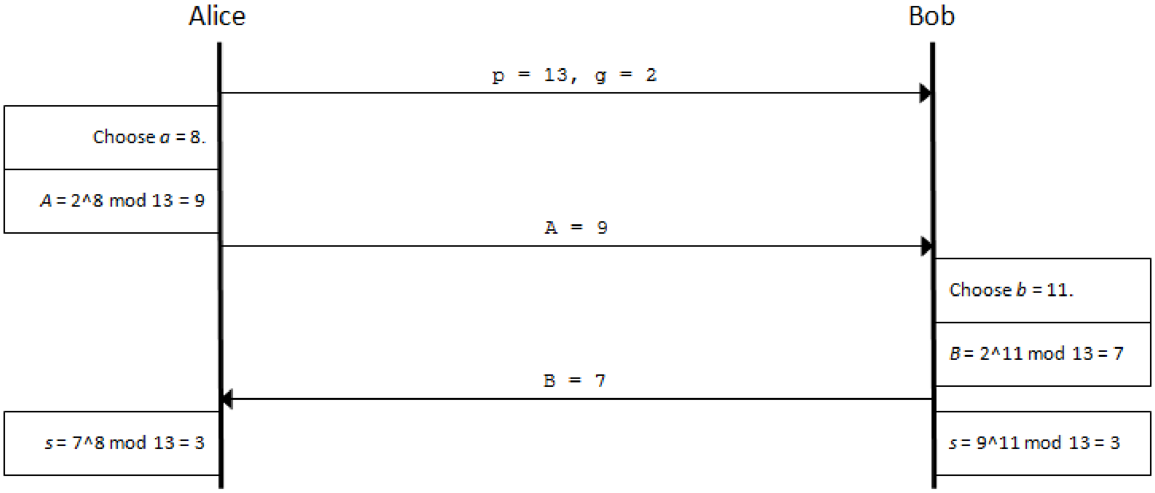


Figure 3.3: Example of the Diffie-Hellman key exchange algorithm. The shared key s is 3. To find the inverse, Bob calculates $A^{(|G|-b)}$ mod $p = 9$ and Alice calculates $B^{(|G|-a)}$ mod $p = 9$.

3.3 Elliptic Curves

An `elliptic curve` is a set of points that satisfies the equation $y^2 = x^3 + ax + b$, where a and b are real numbers. When $4a^3 + 27b^2 \neq 0$, then the curve contains no repeat factors and can be used to form a group. The group consists of the points on the curve an additional point, O, known as the point at infinity. Figure 3.4 shows the curve $y^2 = x^3 + x$. Elliptic curves are symmetrical about the X axis. The negation of a point $P = (x_P, y_P)$ is therefore $-P = (x_P, -y_P)$. For every point P that is part of an elliptic curve group, $-P$ is also part of that group.

The sum of of two points, $R = P + Q$, where $Q \neq -P$, is defined as:

$$\begin{aligned} s &= \tfrac{y_P - y_Q}{x_P - x_Q}, \\ x_R &= s^2 - x_P - x_Q, \\ y_R &= -y_P + s(x_P - x_R). \end{aligned}$$

Note that s is the slope of the line that contains both P and Q. The resulting sum, R, is the inverse of the third point in the elliptic curve that intersects that same line. As the line containing both P and $-P$ is parallel to the Y axis, the sum of P and $-P$ is defined as O, the point at infinity.

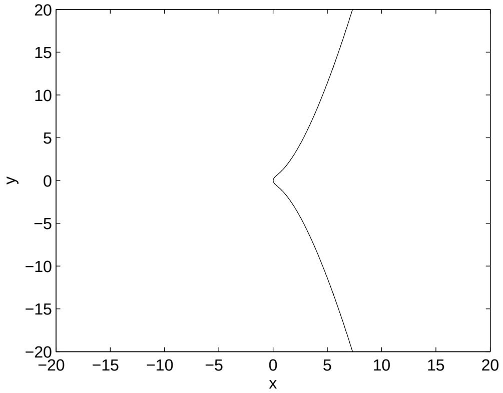


Figure 3.4: The elliptic curve $y^2 = x^3 + x$. Many elliptic curves have a second, disjoint component, but this one does not.

Finally, to add P to itself (or, to double P), then $R = 2P$, where:

$$\begin{aligned} s &= \tfrac{3{x_P}^2+a}{2y_P}, \\ x_R &= s^2 - 2x_P, \\ y_R &= -y_P + s(x_P - x_R). \end{aligned}$$

Here, s is the slope of the line tangent to P, which intersects the elliptic curve at precisely one other point. An exception occurs when $y_P = 0$ because the line tangent to a point on an X axis has a slope of infinity. In this case, $2P = O$. Using the addition rule already described, one can find that $3P = 2P + P = O + P = P$. Continuing in this sense, $4P = O$, $5P = P$, and so on.

Elliptic curves defined in this manner have an infinite number of points. As the points are pairs of real numbers, calculations involving them are slow and prone to rounding errors. Cryptographic applications therefore use elliptic curves defined over finite fields. As with the Diffie-Hellman key exchange described in Section 3.2, operations over such a finite field, $\mathbb{F}_p$, are performed modulo p. The points that satisfy the equation $y^2 \mod p = x^3 + ax + b \mod p$ are elements of the elliptic curve over $\mathbb{F}_p$. As before, when $4a^3 + 27b^2 \mod p \neq 0$, the points on the elliptic curve over $\mathbb{F}_p$ and the point at infinity, O, form a group. Figure 3.5 shows the elements of the elliptic curve $y^2 = x^3 + x$ over $\mathbb{F}_{13}$.

Note that instead of being symmetric about the X axis, an elliptic curve over $\mathbb{F}_{13}$ is

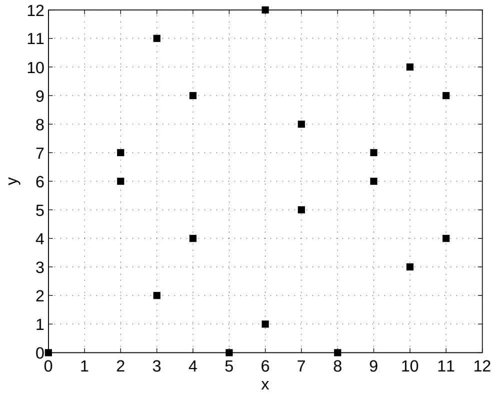


Figure 3.5: The elliptic curve $y^2 = x^3 + x$ over $\mathbb{F}_{13}$. Notice that the line of symmetry is at $y = 6.5$.

symmetric about the line $y = \frac{13}{2}$. Thus, the inverse of a point $P = (x_P, y_P)$ is $-P = (x_P, -y_P \mod 13)$. In Figure 3.5, the points $(5, 0)$ and $(8, 0)$ might look as though they break the symmetry, but in fact they are their own inverses in $\mathbb{F}_{13}$. More generally, for an elliptic curve over the finite field $\mathbb{F}_p$, the line of symmetry is at $y = \frac{p}{2}$ and $-P = (x_P, -y_P \mod p)$. Addition and doubling of points in the finite elliptic curve group follow the same rules as for infinite curves, except that calculations are modulo p.

Recall that the Diffie-Hellman key exchange algorithm relied on the discrete logarithm problem (DLP) for its security. In a similar manner, cryptographic protocols using elliptic curves over finite fields rely on the elliptic curve discrete logarithm problem (ECDLP). Through a combination of point doubling and point addition using the point P, one can find the value of nP. Given two points P and Q, the ECDLP is to find the integer k such that $P = kQ$. As with the original DLP, there is no known efficient algorithm to solve the ECDLP.

For elliptic curve Diffie-Hellman (ECDH), two two parties Alice and Bob must first agree on the following six parameters:

- p The size of the finite field, $\mathbb{F}_p$,

- a The first coefficient in the elliptic curve equation, E,

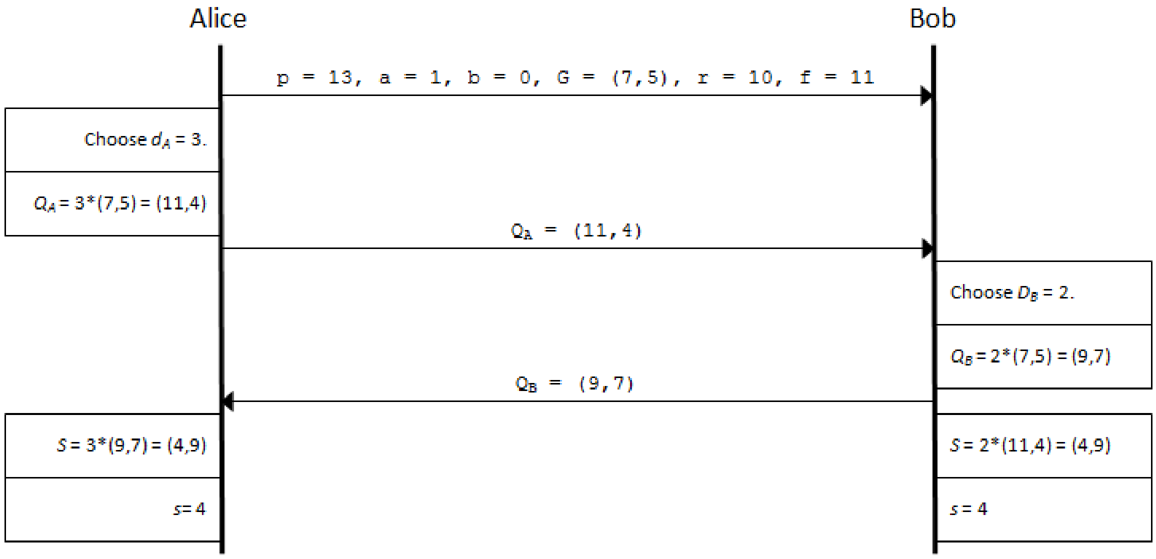


Figure 3.6: Example of the Elliptic Curve Diffie-Hellman key exchange algorithm. The shared key s is 4. Note that the order of G is 10 since $10 * (7,5) = \infty$ and the cofactor is 11 since $\frac{19}{10} \mod 13 = 11$. For cryptographic applications, a cofactor of 1 is ideal since this implies that the entire curve is part of the subgroup generated by G and simplifies calculations.

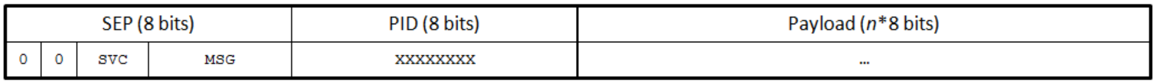
- b The second coefficient in the elliptic curve equation, E,

- G The base point, a point in the group $E(\mathbb{F}_p)$,

- r The order of G, the smallest non-negative integer such that $nG = \infty$,

- f The cofactor, where $n = fr$ is the number of points on the curve.

The values p and r are prime and the parameters are chosen such that f is as small as possible for efficiency reasons. An ECDH keypair consists of the private key d, where d is an integer in the range $[1, r-1]$ and the public key Q, where $G = dQ$. Alice chooses (d_A, Q_A) and sends Q_A to Bob. Bob chooses (d_B, Q_B) and sends Q_B to Alice. Alice then computes $S = d_A Q_B$ and Bob computes $S = d_B Q_A$. The shared secret, s, is the x-coordinate of the point S. Note that $d_A Q_B = d_A d_B G = d_B d_A G = d_B Q_A$, so both parties will always calculate the same value for s. Figure 3.6 shows an example of an ECDH key exchange using small values for clarity.



SEP (8 bits)				PID (8 bits)	Payload (*n**8 bits)
0	0	SVC	MSG	xxxxxxxx	…

Figure 3.7: Format of the NFC-SEC PDU. The PID and Payload fields are not present in all PDUs.

Table 3.1: NFC-SEC PDUs.

Command	MSG	PID?	Payload?	Description
ACT_REQ	0000	Y	C	Request a new secure service.
ACT_RES	0001	N	C	Accept a new secure service.
VFY_REQ	0010	N	C	Verify the sender's shared secret.
VFY_RES	0011	N	C	Verify the recipient's shared secret.
ENC	0100	N	C	An encrypted data packet.
TMN	0110	N	N	Terminate the secure service.
ERROR	1111	N	C	Indicates an error.

3.4 NFC-SEC

Recall from Section 2.3.2.2 that the ATR_REQ command contains a field called PPi, which contains a bit for NFC-SEC. Similarly, the PPt field of the ATR_RES response contains a bit for NFC-SEC. When two NFC devices are establishing a link, they can check the value of these NFC-SEC bits. If both are set to '1', then the two devices can decide to establish a secure link. The ECMA-385 standard [53] defines two security services for NFC devices: the shared secret service (SSE) and the secure channel service (SCH). In the layered protocol stack, the NFC-SEC protocol sits just above the digital interface.

Figure 3.7 illustrates the format of all protocol data units (PDUs) for NFC-SEC. The SVC field is set to "00" for SSE exchanges and to "01" for SCH exchanges. The value of MSG encodes the type of PDU. Note that the PID and Payload fields are not present in all NFC-SEC PDUs. Table 3.1 summarizes the fields and values for each type of NFC-SEC PDU. In this table, 'C' denotes that a field is conditionally present in a PDU. As the NFC-SEC protocol sits above the digital layer described by NFCIP-1, the entirety of each NFC-SEC PDU is transmitted in the Payload field of a NFC PDU during the Data Exchange Protocol (DEP) phase.

As with other NFC protocols, the PDUs are separated into three phases. In the first phase, two NFC-SEC devices establish the secure services. The Activation Request (ACT_REQ) and Activation Response (ACT_RES) PDUs begin the service. Next, the Verification Request (VFY_REQ) and Verification Response (VFY_RES) enable the two devices to ensure that their shared secret is valid. Once the link is established, encrypted messages are sent with the Encrypted (ENC) PDU. To terminate the link, one device sends the Terminate (TMN) PDU. Finally, errors are sent with the ERROR PDU, which always terminates a secure link. Figure 3.8 shows the process of establishing, using, and then terminating the secure services described by NFC-SEC.

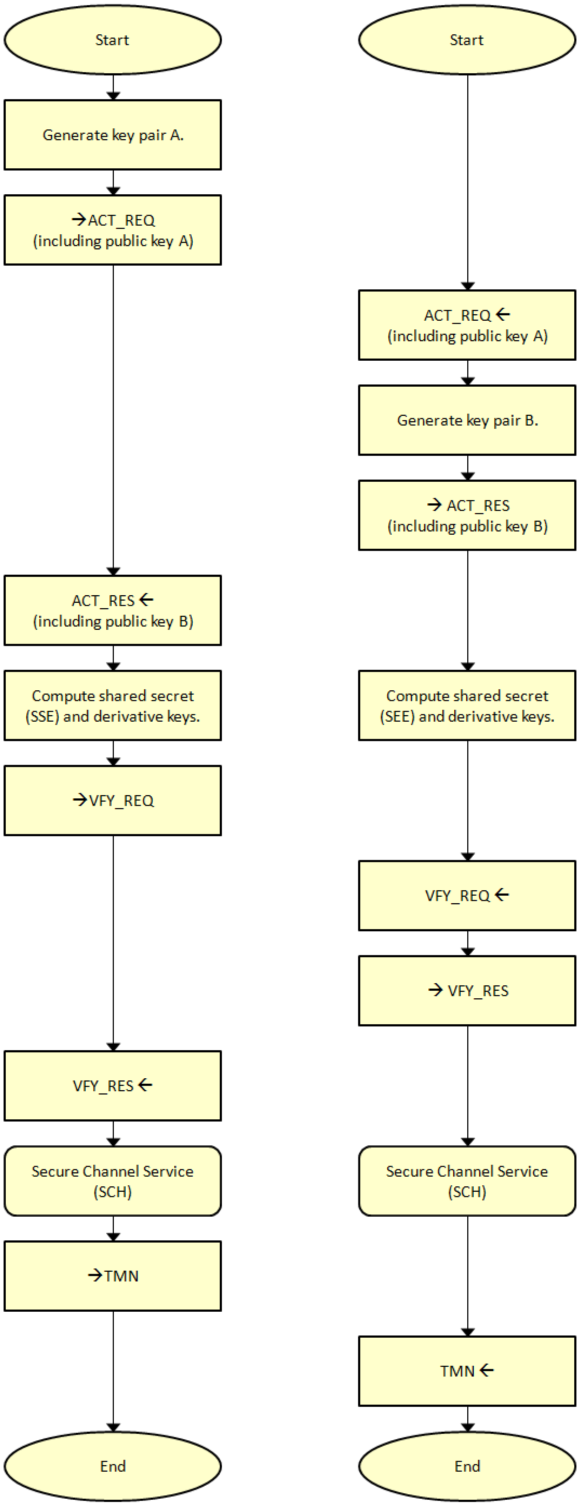


Figure 3.8: Flowchart of the NFC-SEC protocol. Alice, using the NFC device on the left, initiates the secure services and Bob, using the other device, responds. The NFC-SEC protocol does not assume any specific key exchange or encryption protocols.

3.5 NFC-SEC-1

The NFC-SEC protocol described by ECMA-385 [53] does not specify the key exchange or data encryption algorithms to use for the secure services. Instead, these details are left to the user. However, the ECMA-386 standard, NFC-SEC-1 [54], offers one possible implementation of the NFC-SEC security services using the Elliptic Curve Diffie-Hellman key exchange algorithm and AES for data encryption. This implementation of NFC-SEC uses a PID value of 1 for ACT_REQ frames.

The elliptic curve parameters $p, a, b, G, r, \text{and}, f$ are always the P-192 curve defined in FIPS-PUB 186-2. Thus, Alice and Bob do not need to exchange this information to begin a transaction. Instead, Alice first generates a random 96-bit nonce, N_A. She sends this nonce and her public key, Q_A, to Bob as part of the ACT_REQ command. Bob responds with an ACT_RES that contains another 96-bit nonce, N_B, and his public key, Q_B. Then, both participants compute the shared secret Z as described in Section 3.3. This completes the Elliptic Curve Diffie Hellman key exchange.

Next, each peer computes a 128-bit key, MK_{SSE}, which becomes the shared secret for SSE. Alice and Bob each derive this key from $N_A, N_B, Z, ID_A, \text{and} ID_B$ using the following procedure, where ID_A and ID_B are the NFCID3 values for Alice and Bob (see Section 2.3.2.2), the || operator is concatenation, and AES-XCBC-PRF-128 is defined in RFC 4434 [62]:

$$\begin{aligned} S &= N_A[0:63]||N_B[0:63], \\ SEED &= \text{AES-XCBC-PRF-128}(S, Z), \\ MK_{SSE} &= \text{AES-XCBC-PRF-128}(SEED, S||ID_A||ID_B||\text{01h}). \end{aligned}$$

Figure 3.9 shows Alice and Bob establishing the shared secret service.

To establish the secure channel service, SCH, Alice and Bob must repeat the Diffie-Hellman key exchange with new nonces. Then, they derive three more 128 bit keys. The first, MK_{SCH}, is the master key for SCH and is used to derive the other keys. KE_{SCH}, the second key, is used for encrypting data packets. The final key, KI_{SCH}, is used for data integrity. Alice and Bob derive these three keys with the following procedure:

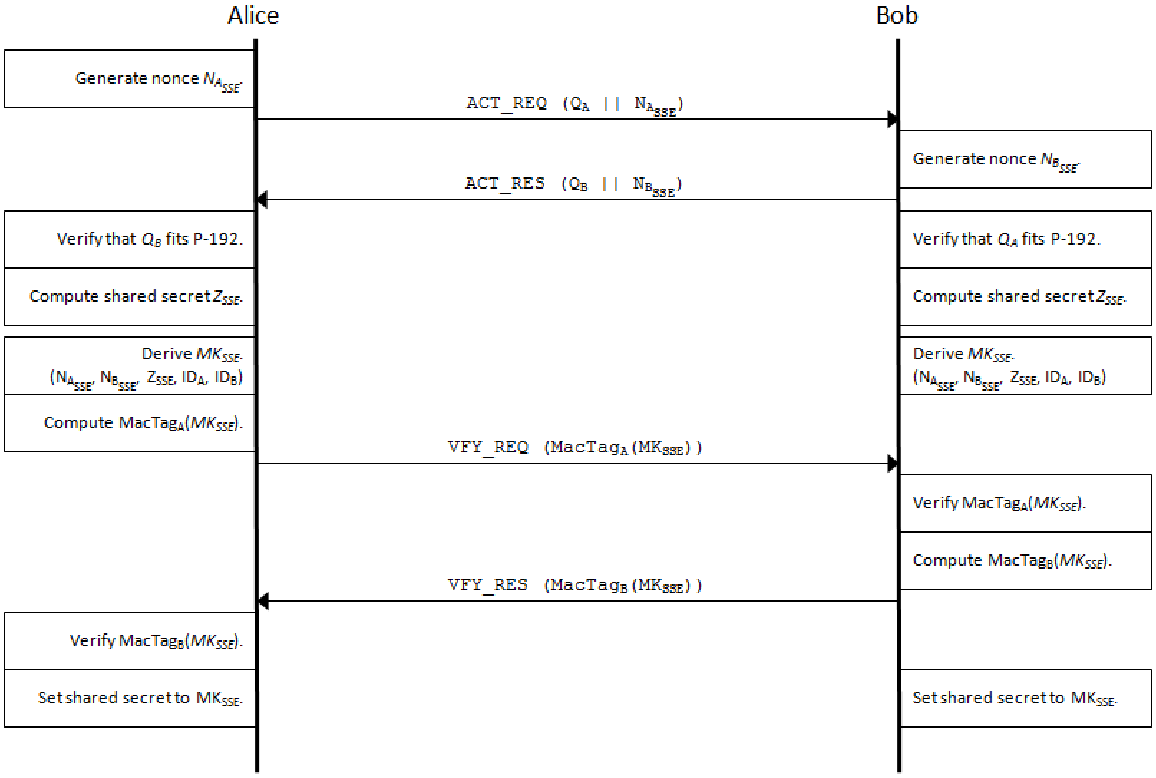

Alice
Bob
Generate nonce $N_{A_{SSE}}$.
ACT_REQ (Q_A || $N_{A_{SSE}}$)
Generate nonce $N_{B_{SSE}}$.
ACT_RES (Q_B || $N_{B_{SSE}}$)
Verify that Q_B fits P-192.
Verify that Q_A fits P-192.
Compute shared secret Z_{SSE}.
Compute shared secret Z_{SSE}.
Derive MK_{SSE}.
($N_{A_{SSE}}$, $N_{B_{SSE}}$, Z_{SSE}, ID_A, ID_B)
Derive MK_{SSE}.
($N_{A_{SSE}}$, $N_{B_{SSE}}$, Z_{SSE}, ID_A, ID_B)
Compute $MacTag_A(MK_{SSE})$.
VFY_REQ ($MacTag_A(MK_{SSE})$)
Verify $MacTag_A(MK_{SSE})$.
Compute $MacTag_B(MK_{SSE})$.
VFY_RES ($MacTag_B(MK_{SSE})$)
Verify $MacTag_B(MK_{SSE})$.
Set shared secret to MK_{SSE}.
Set shared secret to MK_{SSE}.

Figure 3.9: Establishing the NFC SEC 1 shared secret service. First, Alice and Bob perform an elliptic curve Diffie-Hellman key exchange. Then, they derive a new shared secret and verify that they are both using the same key.

$$\begin{aligned}
S &= N_A[0:63]||N_B[0:63] \\
SEED &= \text{AES-XCBC-PRF-128}(S, Z) \\
MK_{SCH} &= \text{AES-XCBC-PRF-128}(SEED, S||ID_A||ID_B||\text{01h}) \\
KE_{SCH} &= \text{AES-XCBC-PRF-128}(SEED, MK_{SCH}||ID_A||ID_B||\text{02h}) \\
KI_{SCH} &= \text{AES-XCBC-PRF-128}(SEED, KE_{SCH}||ID_A||ID_B||\text{03h})
\end{aligned}$$

As each key is generated, Alice and Bob perform a key validation exchange to ensure that the generated keys are correct. First, Alice computes a message authentication code (MAC) for the key using the AES-XCBC-MAC-96 algorithm defined in RFC 3566 [63] with the key in question as the key and $03\text{h}||ID_A||ID_B||Q_A||Q_B$ as the message. Alice then sends this 96-bit value, $MacTag_A(K)$, to Bob using the VFY_REQ command. Bob performs the same calculation and compares the two values. If they match, then Alice has derived the

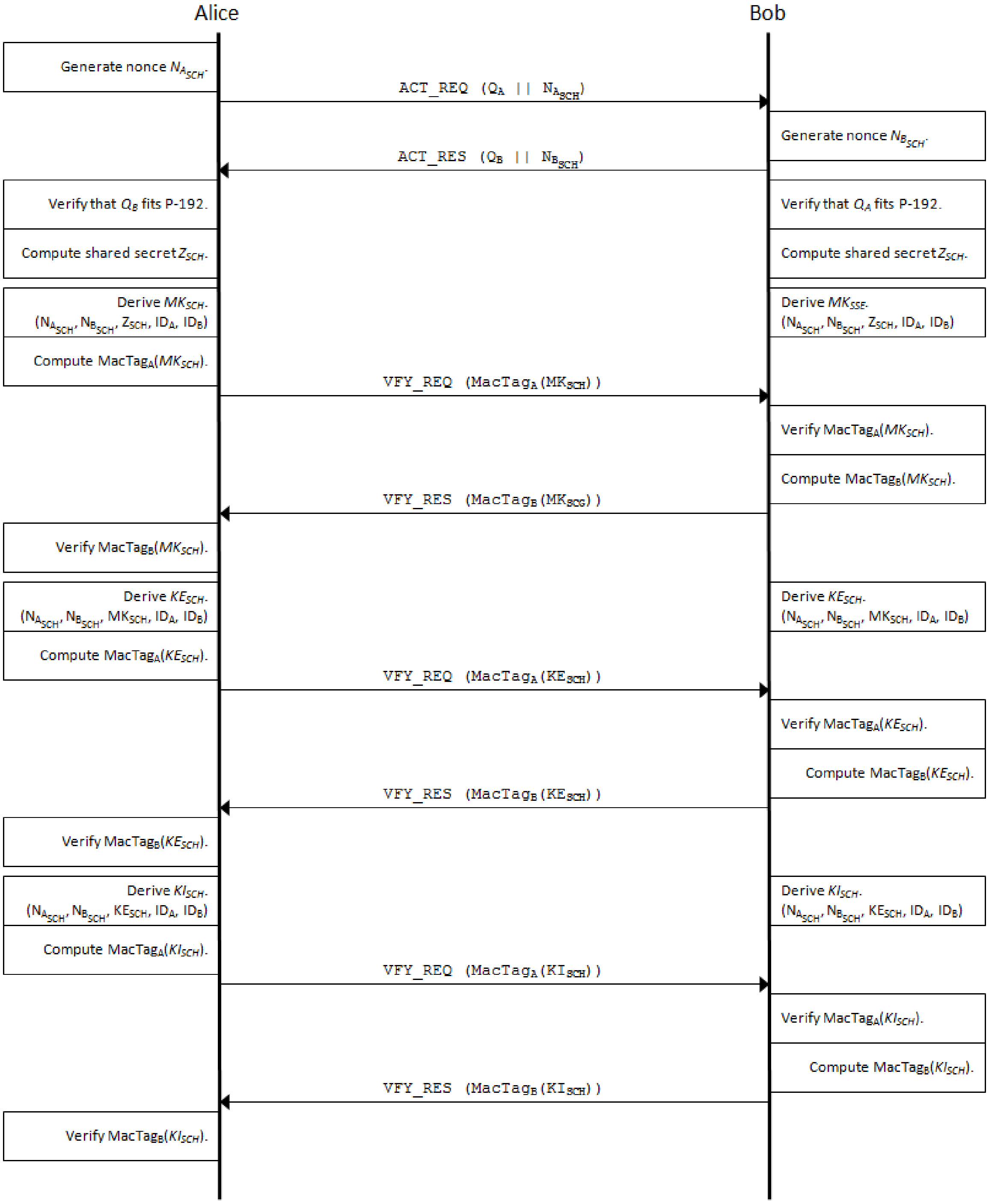

Alice
Bob
Generate nonce $N_{A_{SCH}}$.
ACT_REQ (Q_A || $N_{A_{SCH}}$)
Generate nonce $N_{B_{SCH}}$.
ACT_RES (Q_B || $N_{B_{SCH}}$)
Verify that Q_B fits P-192.
Verify that Q_A fits P-192.
Compute shared secret Z_{SCH}.
Compute shared secret Z_{SCH}.
Derive MK_{SCH}.
($N_{A_{SCH}}$, $N_{B_{SCH}}$, Z_{SCH}, ID_A, ID_B)
Derive MK_{SSE}.
($N_{A_{SCH}}$, $N_{B_{SCH}}$, Z_{SCH}, ID_A, ID_B)
Compute $MacTag_A(MK_{SCH})$.
VFY_REQ ($MacTag_A(MK_{SCH})$)
Verify $MacTag_A(MK_{SCH})$.
Compute $MacTag_B(MK_{SCH})$.
VFY_RES ($MacTag_B(MK_{SCG})$)
Verify $MacTag_B(MK_{SCH})$.
Derive KE_{SCH}.
($N_{A_{SCH}}$, $N_{B_{SCH}}$, MK_{SCH}, ID_A, ID_B)
Derive KE_{SCH}.
($N_{A_{SCH}}$, $N_{B_{SCH}}$, MK_{SCH}, ID_A, ID_B)
Compute $MacTag_A(KE_{SCH})$.
VFY_REQ ($MacTag_A(KE_{SCH})$)
Verify $MacTag_A(KE_{SCH})$.
Compute $MacTag_B(KE_{SCH})$.
VFY_RES ($MacTag_B(KE_{SCH})$)
Verify $MacTag_B(KE_{SCH})$.
Derive KI_{SCH}.
($N_{A_{SCH}}$, $N_{B_{SCH}}$, KE_{SCH}, ID_A, ID_B)
Derive KI_{SCH}.
($N_{A_{SCH}}$, $N_{B_{SCH}}$, KE_{SCH}, ID_A, ID_B)
Compute $MacTag_A(KI_{SCH})$.
VFY_REQ ($MacTag_A(KI_{SCH})$)
Verify $MacTag_A(KI_{SCH})$.
Compute $MacTag_B(KI_{SCH})$.
VFY_RES ($MacTag_B(KI_{SCH})$)
Verify $MacTag_B(KI_{SCH})$.

Figure 3.10: Establishing the NFC SEC 1 secure channel service. First, Alice and Bob perform an elliptic curve Diffie-Hellman key exchange. Then, they derive the master key and verify that they are both using the same key. Finally, they dervice the data encryption and data integrity keys and verify those, too.

key correctly. In response, Bob calculates $MacTag_B(K)$ using the same procedure and 02h$||ID_B||ID_A||Q_B||Q_A$ as the message. Bob sends a VFY_RES response to Alice, who checks the key's validity. This process is illustrated by Figure 3.10.

Once all four keys are validated, Alice and Bob can begin to exchange data. Data is encrypted using AES in Counter Mode [64]. The initial value of the 128 bit counter is calculated using the AES-XCBC-PRF-128 algorithm with the key set to MK_{SCH} and the message set to $KI_{SCH}||N_A||N_B||$04h. Each peer calculates this value independently so that it is never sent over the channel. For each message, the value of counter is first encrypted using AES-XCBC-PRF-128 with KE_{SCH} as the key. Then, the encrypted counter value is exclusive-OR'd with the message plaintext to form the final ciphertext, which Alice can send to Bob. At the end of the operation, the value of the counter is increased by one. When Bob receives the message, he performs the same AES operation on his counter value, which should be equal to Alice's, and again performs the exclusive-OR operation to recover the message plaintext. Bob also increments his counter value.

To ensure that arriving data is in the proper sequence, each peer maintains a counter (SNV) that increases by one for each encrypted message sent or received. This counter is initialized to zero and has a maximum value of $2^{24} - 1$. When the maximum value is reached, the secure services must be terminated. Finally, the integrity of each message guaranteed with a MAC using KI_{SCH} as the key and SNV||Data_Length||Encrypted_Message as the message. The MAC is concatenated to the end of SNV, Data_Length, and Encrypted_Message to form the ENC PDU payload. Figure 3.11 shows the process of sending encrypted data using the NFC-SEC-1 protocol.

3.6 Chapter Summary

The NFC-SEC and NFC-SEC-1 specifications utilize industry standard cryptographic protocols to secure NFC communications. By providing both a shared secret service and a secure channel service, users of NFC devices can ensure that they are communicating with their intended target and that their messages are secure from eavesdropping attacks.

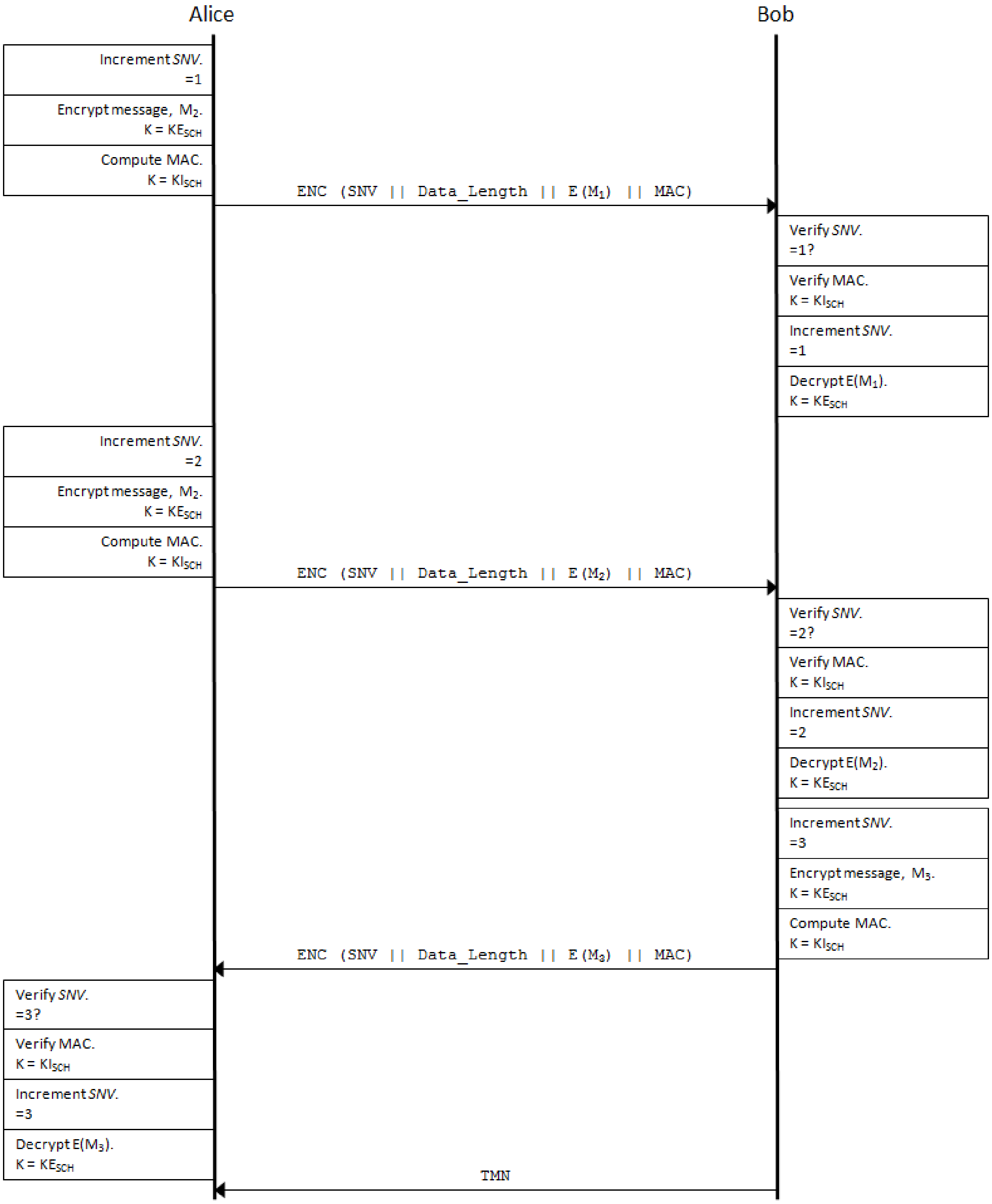

Alice
Bob
Increment *SNV*. =1
Encrypt message, M_2. $K = KE_{SCH}$
Compute MAC. $K = KI_{SCH}$
ENC (SNV || Data_Length || E(M_1) || MAC)
Verify *SNV*. =1?
Verify MAC. $K = KI_{SCH}$
Increment *SNV*. =1
Decrypt E(M_1). $K = KE_{SCH}$
Increment *SNV*. =2
Encrypt message, M_2. $K = KE_{SCH}$
Compute MAC. $K = KI_{SCH}$
ENC (SNV || Data_Length || E(M_2) || MAC)
Verify *SNV*. =2?
Verify MAC. $K = KI_{SCH}$
Increment *SNV*. =2
Decrypt E(M_2). $K = KE_{SCH}$
Increment *SNV*. =3
Encrypt message, M_3. $K = KE_{SCH}$
Compute MAC. $K = KI_{SCH}$
ENC (SNV || Data_Length || E(M_3) || MAC)
Verify *SNV*. =3?
Verify MAC. $K = KI_{SCH}$
Increment *SNV*. =3
Decrypt E(M_3). $K = KE_{SCH}$
TMN

Figure 3.11: Sending encrypted data with NFC SEC 1. Alice and Bob use the keys that they generated in Figure 3.10 to encrypt their data and to ensure that they receive unaltered frames. Here, Alice sends Bob two frames. Bob responds with a single frame and then terminates the secure services.

Chapter 4

NFC Protocol Security

Due to their very nature, all wireless systems are vulnerable to a set of attacks that includes eavesdropping, denial of service, and relays. NFC is no exception. In 2006, Ernst Haselsteiner and Klemens Breitfuß of Philips Semiconductors looked at a number of threats to NFC systems [65]. This chapter examines those threats and others, evaluates NFC's specific vulnerabilities and defenses in regards to threats, and details previous attempts to compromise NFC systems.

4.1 Eavesdropping Attacks

Just as one might stand outside of a door and listen to two people conversing on the other side, so too can one eavesdrop on two devices communicating wirelessly. In Figure 4.1, Alice and Bob are exchanging data while Eve listens in. Since Eve is not transmitting, Alice and Bob might not know that she is there at all. Silently, Eve can collect information from Alice and Bob.

The data that Eve collects might be sensitive. For instance, Alice might be a card reader and Bob might be an emulated NFC-enabled credit card [14][15]. In this case, Eve may be able to collect credit card numbers and personal contact information. Or, perhaps Alice and Bob comprise a lock and key system [10]. If Eve is able to eavesdrop on their communications, then she might be able to obtain the password for entry. In these and other cases, the designers of NFC systems have an obligation to protect customer data.

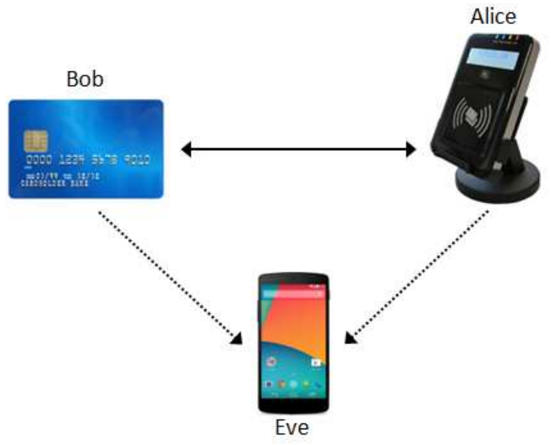


Figure 4.1: Example of an eavesdropping attack. Here, Alice is the NFC card reader and Bob is a NFC-enabled credit card. Eve is a cell phone placed close to the card reader, perhaps by the cashier. Eve might be able to collect credit card numbers and personal contact information [66][67][68].

Since [65] was published in 2006, ECMA has introduced the NFC-SEC protocol described in Sections 3.4 and 3.5 [53]. This protocol provides a secure channel for Alice and Bob to ensure that Eve can only collect encrypted information. With a proper implementation, such as [54], decrypting that information would be nearly impossible. Thus, for systems in which encryption is appropriate, NFC-SEC provides solid defense against eavesdropping attacks. Nevertheless, not all systems are able to use the NFC-SEC protocols. For these systems, we must consider the maximum eavesdropping range.

As [65] notes, the equipment required to receive and decode NFC messages is commonly available. Indeed, the NFC Forum's ANALOG specification [36] provides reference schematics and PCB layouts for multiple NFC devices. Thus, we must assume the existance of Eve. However, constructing Eve might still be difficult. NFC devices operate on a range of less than 10 cm. In order to use an ordinary NFC device for eavesdropping, it must be within 10 cm of both Alice and Bob. Such a device is likely visible to Alice and Bob's users.

Recall from Section 2.2 that the 10 cm range is largely a limitation imposed by the small antennas used in portable devices. With a larger antenna, the eavesdropping range increases. Haselsteiner and Breitfuß estimated the maximum eavesdropping range to be 10 meters for NFC devices communicating in active mode and 1 meter for devices using the passive mode [65].

In [69], Brown *et al.* construct an experiment in which they emulate a transmitting NFC device with a one turn circular coil antenna with a radius of 1.5 cm. This device transmitted a square wave at 108 kHz in order to approximate an active $^{f_c}/_{128}$ device using 100% ASK. Using a second antenna similar to the first, the authors were able to receive and decode the square wave signal at a distance of 0.5 meters when the transmit field strength was set to 0.5 A/m. At a strength of 1.5 A/m, the authors were able to receive a signal at a distance of 0.7 meters and at 4.5 A/m, a distance of 0.9 meters.

The NFCIP-1 specification requires a minimum RF field strength of 1.5 A/m and allows a maximum strength of 7.5 A/m [33]. Thus, the experiments in [69] show that the eavesdropping range for active NFC devices at $^{f_c}/_{128}$ is longer than 10 cm. Indeed, at the required minimum RF strength of 1.5 A/m, the eavesdropping range is approximately 7x the normal operating range. At higher strengths, the range is even longer.

In addition to the above experiments, Brown *et al.* constructed a second setup in which they used a shopping cart as the eavesdropping antenna. In this scenario, they were able to receive the emulated NFC signal at a range of 0.3 meters when the transmit field strength was 1.5 A/m and 0.4 meters at a strength of 4.5 A/m. This distance is not the 10 meters predicted by [65], but it might be far enough for a clever customer to use his shopping cart as an eavesdropping antenna to record payment transactions. Further, it shows that an eavesdropping antenna need not always be precisely designed.

As noted in [65] and [70], the eavesdropping range of passive NFC communications should be smaller than it is for active communications. In [71], the authors conduct an experiment in which they use an off-the-shelf NFC-enabled cellular phone and a typical NFC card reader to conduct transactions in passive mode. In addition, they construct two eavesdropping antennas by attaching an oscilloscope to both a MiFare UltraLight label and a MiFar Classic card. After performing the experiments with the antennas placed in numerous positions, the author concludes that the maximum eavesdropping range for passive NFC communications is approximately 0.3 meters.

The experiments in [69] and [71] demonstrate that NFC's maximum operating range of

10 cm is not a sufficient defense against eavesdropping attacks. While neither experiment achieved the predicted eavesdropping range of 10 meters, better antenna design increases the maximum eavesdropping range significantly. In [72], Hancke was able to eavesdrop at ranges of up to 15 meters with large, commercially-avaiable antennas. While such setups might not be practical for eavesdropping on credit card transactions, they could instead be used to skim the same data from passersby with NFC-enabled cards in their wallets.

4.2 Data Alteration Attacks

A second classification of attacks are those that modify the data that a NFC device receives. Haselsteiner and Breitfuß consider three variations of data alteration in [65]: data corruption, data modification, and data insertion. The simplest of these is data corruption. In this attack, a rogue device transmits data on the 13.56 MHz frequency at such a strength that any other data transmitted on that frequency would be corrupt. Alternatively, a device could continuously generate a strong 13.56 MHz signal, preventing NFC devices from turning on their own RF fields. As noted in Section 2.3.2, a NFC device executes the “Initial RF Collision Avoidance” protocol before enabling its RF field. If it detects another field with a strength of at least 0.1875 A/m (rms), then it does not turn on its own field [33]. The result of both attacks is a denial of service.

NFC offers no protection against a denial-of-service attack. However, NFC devices are able to detect other RF fields, so such attacks should always be detectable [65]. Nevertheless, these simple attacks could prevent proximity cards from functioning properly, prevent the NFC payment transactions from completing, and prevent the transmission of important medical data.

Data modification attacks are more complex and their feasability depends on both the data rate and transmission mode that the victim devices employ. Active devices operating at ${}^{f_c}/_{128}$ employ a modified Miller encoding with 100ASK modulation (see Figure 2.4). In this scenario, the RF field is either at full strength or it is off. When the field is off, a rogue device could fill the pause with a signal at full strength. However, when the field is at full strength, the attacker has no practical way to cancel out that signal. Thus,

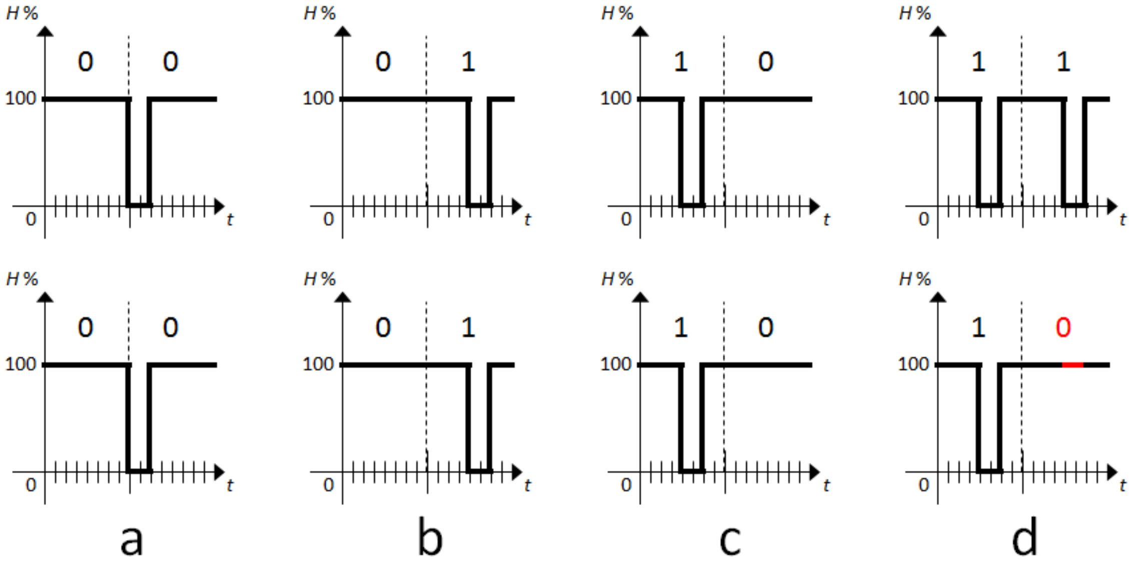


Figure 4.2: Data modification attack at 100% ASK, as employed by an active NFC device operating at ${}^{f_c}/_{128}$. In scenarios *a* and *b*, the rogue device detects a '0' bit and does nothing. At best, the attacker could cause data corruption by causing the receiver to detect two consecutive bit periods with no pauses, but this is equivalent to the data collision attack discussed previously. In scenario *c*, the rogue device detects a '1' and turns on its RF field for the next bit period. However, the next bit was already a '0', so the data arrives at the receiver unchanged. In scenario *d*, the rogue detects a '1', turns on its RF field, and changes the next '1' bit into a '0' bit. The receiver sees a valid bit sequence and does not know that the data has been changed.

data modification in the active, ${}^{f_c}/_{128}$ mode is only possible for two consecutive '1' bits. Figure 4.2 demonstrates this.

In all other communication modes, NFC devices use a 10% ASK modulation scheme in which the signal levels are 100% and 82%. Here, a rogue device could add a signal to the transmitted 82% signals such that that the receiver sees the 82% signals as 100% and the 100% signals as 82%. Since the NFC specification allows a large range for the RF field strength (1.5-7.5 A/m [33]), such an attack seems plausible. However, the rogue device would need to predict when the transmitter sent an 82% signal quickly enough to change its value.

These data modification attacks are easily defeated. NFC-SEC offers data integrity mechanisms, so devices utilizing this protocol could detect any data modifications. For

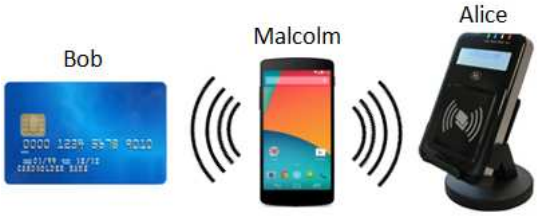


Figure 4.3: A man-in-the-middle attack with NFC devices. Here, Malcolm intercepts messages from both Alice and Bob without their knowledge. Due to NFC's short operating range, this type of attacks is nearly impossible to perform.

devices that do not support NFC-SEC, a simple cyclic redundancy check (CRC) is sufficient to ensure that the data has likely not been modified.

Finally, the authors in [65] consider data insertion attacks. In this attack, a rogue device transmits data before the victim device can do so. For intance, an Initiator might send out a request and then wait for the Target device to respond. If the rogue device can respond before the Target does, then it can trick the Initiator into using false data. This sort of attack only works when one device pauses for a response and only when the rogue device can respond faster than the victim device. Chapter 6 considers a situation in which more than one device responds to an Initiator's request.

4.3 Man-in-the-Middle Attacks

A typical man-in-the-middle attack involves three devices. The two victim devices, Alice and Bob, wish to communicate. However, the rogue device, Malcolm, tricks Alice and Bob into a three-party conversation [65][70]. When Alice attempts to set up a link with Bob, she really sets up a link with Malcolm. Malcolm then sets up a second link with Bob. In this way, Malcolm can intercept all messages sent by both Alice and Bob. Figure 4.3 demonstrates this scenario with NFC devices.

If Malcolm can read a message from Alice and Bob, then he might also be able to modify that message before sending it along to its intended recipient. Further, Malcolm can store the message contents for later. Using a secure channel service, such as the one specified in by the NFC-SEC protocols [53][54], would not prevent Malcolm from performing a man-in-the-middle attack. Rather, Malcolm would simply establish two secure channels, one each with Alice and Bob. One counter to this problem lies with authentication services, in which public keys are verified by a third-party. NFC-SEC does not require such authentication.

Nevertheless, NFC does offer strong defenses against man-in-the-middle attacks. Consider the situation in Figure 4.3. Here, Alice is an active device, Bob is a passive device, and Malcolm can use both modes. To begin the transaction, Alice sends a message to Bob, which Malcolm intercepts. At the same time, Malcolm must also ensure that Bob does not receive Alice's message. If Malcolm disturbs the transmission such that Bob cannot read it, then Alice would be able to detect Malcolm's transmissions and she could then stop the transaction. However, let us assume that Alice does not check for this distruption since NFCIP-1 [33] does not require it. Once Malcolm has the message from Alice, he must relay that message to Bob. In doin so, Malcolm must enable his RF field. Since Bob is a passive device, Alice will have left her RF field on so that Bob use it to respond. With two active RF fields, Bob will not likely be able to understand the message that Malcolm relays.

What about two active devices? As with the previous scenario, Malcolm must first disturb Alice's transmission so that Bob cannot receive it. Again, Alice could check for this disturbance and stop the transaction. As before, let us assume that she does not perform this check. This time, Alice turns off her RF field so that Bob can use his own field to respond. Next, Malcolm must relay Alice's message to Bob. When he does so, both Bob and Alice will receive that message. Alice can again detect a problem since Malcolm's message was not what she expected from Bob.

In either case, a man-in-the-middle attack with three NFC devices is simply not feasbile. In order for it to work, Alice and Bob would need to be far enough apart so that they could not detect each other and Malcolm would have to move such that he is only ever within range of either Alice or Bob. Since NFC devices operate with a range of only 4-10 cm, a device capable of performing such feats would almost certainly be detectable by the parties in control of Alice and Bob.

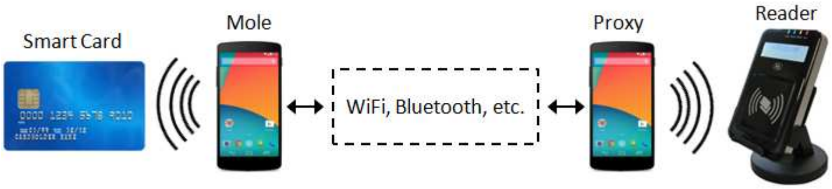


Figure 4.4: A typical relay attack with NFC devices. Here, the proxy device relays commands from the NFC card reader to the mole, who then relays those commands to the smart card. In the other direction, the mole relays the smart card's responses to the proxy, who in turn relays them to the card reader.

4.4 Relay Attacks

A relay attack overcomes NFC's primary defenses by adding a fourth device to the mix. In a typical relay attack, Alice and Bob are separated by enough distance such that they could not communicate. Instead, a rogue device, here called the proxy, communicates with Alice while a second rogue device, here called the mole, communicates with Bob. The two rogue devices communicate with each other via Ethernet, WiFi, Bluetooth, or some other technology. In this way, the rogue devices can relay commands from Alice to Bob and similarly relay Bob's responses back to Alice. Figure 4.4 illustrates the relay attack concept.

Relay attacks are potent. As with man-in-the-middle attacks, either the proxy or the mole can read or modify the communications between Alice and Bob. NFC-SEC offers protection against these actions. However, relay attacks have a second purpose. Consider a NFC-enabled card reader located in a coffee shop. A customer with a NFC-enabled smart phone wishes to pay for her coffee, so she brings her phone within range of the card reader. The card reader begins the exchange by sending an identification command to the phone. Instead of replying to the card reader, the customer's phone, which is really acting as a proxy, relays the command over Bluetooth to a cell phone located elsewhere in the coffee shop. This second phone, the mole, receives the command and relays it once more to a smart card that belongs another, unsuspecting customer. When the card responds, the two rogue devices relay that response back to the card reader. This process repeats until the transaction is complete. Using a relay attack, the customer at the register was able to purchase her coffee with another customer's card. Note that since the two rogue devices simply relayed messages, NFC-SEC and other security protocols would not have prevented the relay attack.

There have been numerous relay attacks on NFC devices. In [73], Francis, *et al.* devise a relay attack using four NFC-enabled mobile phones. Alice and the proxy were Nokia 6212 Classic phones [74], while Bob and the mole were Nokia 6131 phones [75]. Each of these phones runs the Nokia Series 40 operating system and supports Java applications. In order to demonstrate the relay attack, the authors established a Bluetooth link between the proxy and the mole and wrote custom Java applications to send messages in both directions through the relay train. While this attack was not connected to any real-world systems, it nevertheless showed that NFC devices, like other wireless systems, are vulnerable to relay attacks.

The phones used in the attack presented in [73] were some of the first phones to support NFC and both are now discontinued. However, modern systems are still susceptible to relay attacks. Authors Wang, *et al.* describe a relay attack in [76] that uses HTC One X [77] smart phones running Google's Android 4 operating sytem and the Android Beam application. Android Beam uses NFC to establish a Bluetooth link between two devices. Many applications shipped on modern Android smart phones used Beam to communicate, including YouTube and Chrome [76]. In this attack, Beam is used to establish Bluetooth links between Alice and the proxy and between the mole and Bob while the link between the two rogue devices runs over WiFi. As in the previous attack with Nokia phones, the authors are able to relay messages from Alice to Bob via the proxy and mole pair.

Another application on modern Android smart phones that uses NFC is Google Wallet. The Google Wallet application interfaces with JavaCard applets on the phone's secure element that store credit card and other payment information. With Google Wallet, customers can use their phones to pay for purchases at NFC-enabled terminals. In [78], Roland, *et al.* demonstrate a relay attack that works with Google Wallet. Using a commercial, off-the-shelf point of sale terminal and a MasterCard PayPass credit card supporting EMV Mag-Stripe security, the authors were able to demonstrate a successful relay attack. Google patched the Wallet application in September 2012 to prevent this specific attack, but it might yet be vulnerable to other forms of attack.

Often, the major limiting factor for any of the above relay attacks is distance. In order to communicate with the victim's smart card or NFC device, the mole must be within operating range, which is typically less than 10 cm [28]. Therefore, the attacker operating the mole device might have to be uncomfortably close to his victim. Indeed, contactless smart cards rely on this short operating range to ensure that the card's owner is in fact present at the point of sale. But what if the range was not so limited?

In [79], Kfir and Wool devise NFC devices that are capable of transmitting and receiving NFC messages at much longer distances than 10 cm. To do so, they wrapped loops of wire around an otherwise unmodified NFC device. Then, they connected the wire to a set of power amplifiers and filters. Finally, they added an optimally-sized antenna made from copper tubing. This device acted as a proxy and was capable of interacting with the card reader at distances of up to 50 meters. For an NFC transaction in which both Alice and Bob would be active devices, two of these proxy devices are sufficient to carry out a long-distance relay attack.

However, in the case of a smart card transaction, the mole communicates with a passive device. To do this, the mole must first power the smart card, which is only possible when the card is within the mole's reactive near field (see Figure 2.1), which limits the maximum distance between the mole and the smart card to only 3.52 meters. In fact, due to constraints on antenna size and power, Kfir and Wool were only able to increase the reliable communication range to 40 cm with a mole device similar to their proxy device [79]. With access to the NFC device driver software and expensive signal processing components, they were able to increase this range further to 55 cm.

The relay attack in [79] was still limited by the distance between the proxy and the mole. After all, the connectivity options commonly found on NFC-enabled devices, such as Bluetooth and WiFi, are themselves designed only to work at distances of less than 100 meters [29][30]. In "Long Distance Relay Attack" [80], authors attempt to remove this limitation by introducing more devices to the attack architecture. Figure 4.5 illustrates this new approach. With the expanded relay attack architecture, Sportiello and Ciardulli were able to demonstrate a relay attack over a distance of $\sim$541 km with an ePassport in Italy

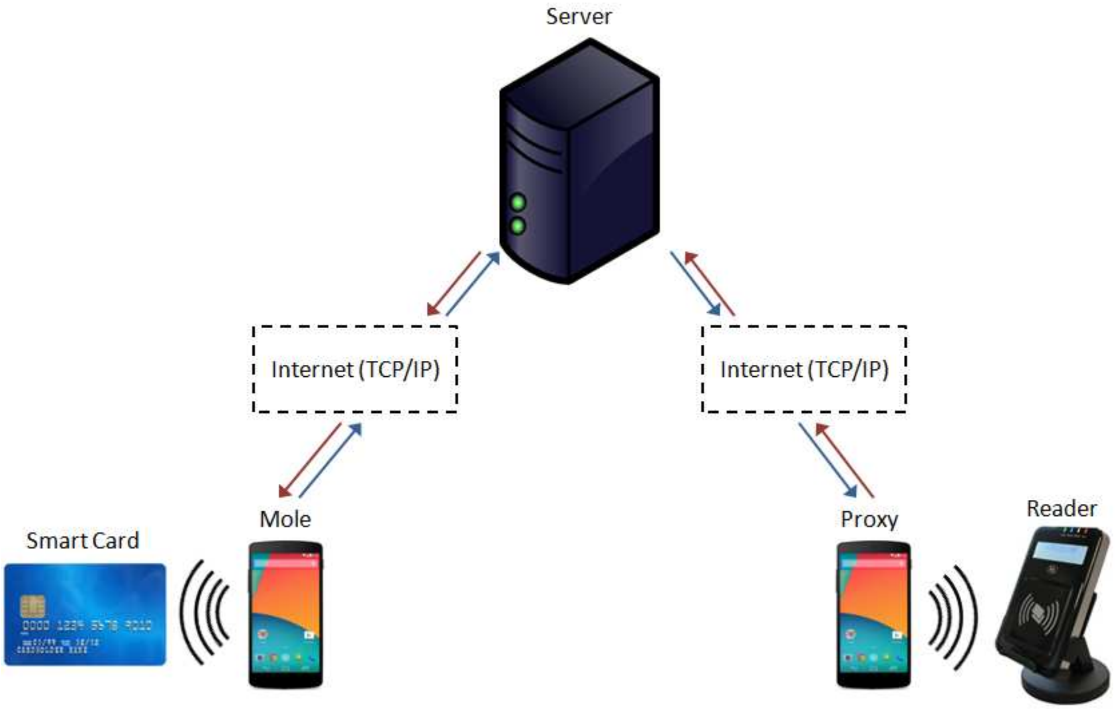


Figure 4.5: A long distance relay attack with NFC devices. In this architecture, the proxy and mole relay their messages through TCI/IP connections with a server that is controlled by the attackers, thereby dramatically increasing the overall distance between the proxy and the mole [80].

and a card reader in Austria!

If we combine the results of “Long Distance Relay Attack” with those of Kfir and Wool, we have a relay attack architecture that works over very long distances and that does not require immediate proximity for either the smart card or the card reader. Each of the devices designed in [79] was valued at less than $100 USD (in 2005) and required only minimal knowledge of how NFC works. Similarly, the long distance attack used only cheap, off the shelf components and simple programs. Therefore, we must assume that such devices are commonly available to would-be attackers.

Given that NFC, like any other wireless protocol, is so vulnerable to relay attacks, software applications utilizing NFC must take extra steps to ensure the authenticity of users and data. Many applications, including Google Wallet, require the user to activate enable the NFC antenna with a PIN. While PINs do increase security, they also increase the amount of time needed to complete a transaction. As speed and convenience are two of NFC's primary selling points, a PIN system might not be appropriate for all applications [80][78].

Another simple solution to the relay attack problem is the faraday cage [78]. If a smart card is enclosed in metal, such as aluminum foil, then a mole will have extreme difficulty communicating with it. Faraday cages are already in use for some systems. Indeed, many proximity cards (*e.g. security badges, green cards*) come with metal envelopes. Unfortunately, this solution is not practical in all cases. Whether for style, simplicity, cost, or other reasons, most of us do not carry metallic purses and wallets. Thus, most smart cards and other NFC/RFID devices (*e.g.* ePassports) remain vulnerable.

The attacks against EMV, Google Wallet, and ePassports worked because these specifications allow for long response delays. In some cases, these long delays are necessary. For instance, a passive device might need to perform a cryptographic operation in response to a command from an active card reader [80]. For this reason, ISO 14443 [40] allows the responding device to ask for as much as ∼4.95 seconds to respond to a command. With current technology, five seconds is a very long time. Certainly, it is enough time to relay messages across the world via the Internet. Therefore, applications should implement tighter time controls for transactions that are not likely to need so much time for processing.

To combat the long distance relay attack, one might imagine using GPS location data to ensure that the two NFC devices are located within the expected 10 cm range. Indeed, [76] and [73] do suggest doing just that. However, GPS technology is not reliable at distances of less than a few meters [81] and it is even less reliable indoors since microwaves are attenuated and scattered by many common building materials. Thus, relay attacks within a shop might still be viable.

A second approach to combating the long distance relay attack involves sensors. Modern smart phones contain many sensors that the payment application could query. In [82], Halevi *et al.* use ambient sound and light data to determine whether the card reader and smart card are in the same location. With audio, the authors reported a 100% success rate for detecting when the two devices are in different locations. With light, they report about a

90% success rate. In both cases, sensor data makes the job of a would-be relay attacker significantly more difficult.

However, the authors in [82] used two phones of the same model to record their audio and light data. Replacing one phone with a card reader, which likely has different sensors and processing chips, might significantly weaken their results. Further, these sensing techniques might have little promise if the attacker is in the same general location as the card reader.

Another attempt at using sensor data attempts to improve upon these results by using temperature sensors [83], Urien and Piramuthu devise an experiment in which both the card reader and the smart card are equipped with temperature sensors. In theory, both sensors should measure the same temperature when the card is placed in close proximity to the reader. When the reader detects a card, it begins a key exchange based on Elliptic-Curve Diffie Hellman (see Sections 3.2). A combination of secret keys, random nonces, and the temperature data allow the two devices to establish a shared secret. If the temperatures are not within the set tolerance, then the transaction is aborted. Otherwise, the two devices begin a time-limited exchange of bits. In order to prevent replay attacks, this bit exchange includes some information that should be secret. With a combination of temperature data and the time-limited exchange, the authors conclude that their approach makes relay attacks on NFC devices nearly impossible.

4.5 Chapter Summary

Near Field Communication, like any other wireless protocol, is vulnerable to a number of attacks. These attacks can allow malicious actors to obtain sensitive information, falsify credentials, and deny service to legitimate users. The short operating range of NFC devices provides good defense against some of these attacks, especially the man-in-the-middle attack. The NFC-SEC protocols provide solid defense against eavesdropping and data alteration attacks for systems in which secure channels are appropriate, though systems that cannot implement NFC-SEC are still vulnerable. Finally, a combination of sensor data and time-limited challenges provides great defense against relay attacks. Generally, NFC, when combined with application-level security, is fairly robust against common attacks.

Chapter 5

NFC Testing Platform

In order to test the security of modern NFC devices, I created the NFC teting platform described in this Chapter. The NFC testing platform consists of modern, open-source hardware (Section 5.1) and free, open-source software (Section 5.2). This combination makes it the ideal platform for academic experimentation.

5.1 Hardware

The hardware for the NFC testing platform consists of a small computing board, three NFC-enabled devices, and a number of supporting elements. The hardware was selected with three criteria in mind: availability, affordability, and similarity to real-world NFC devices. Figure 5.2 is a photograph of the NFC testing platform's primary hardware components, which are:

- *PandaBoard ES*: The large board in the top-right corner of Figure 5.2 is a PandaBoard ES [84]. This fairly inexpensive (less than US$200 at the time of this writing) platform contains hardware similar to that found in mobile phones and other NFC-enabled devices. At the heart of the PandaBoard ES is a Texas Instruments OMAP4460 system on chip (SoC), which contains a dual-core ARM Cortex-A9 microprocessors, an OpenGL ES v2.0 compatible graphics core, and 2 GB of system memory. Other features include 802.11b/g/n WiFi, Bluetooth v2.1 EDR, HDMI outputs, two USB

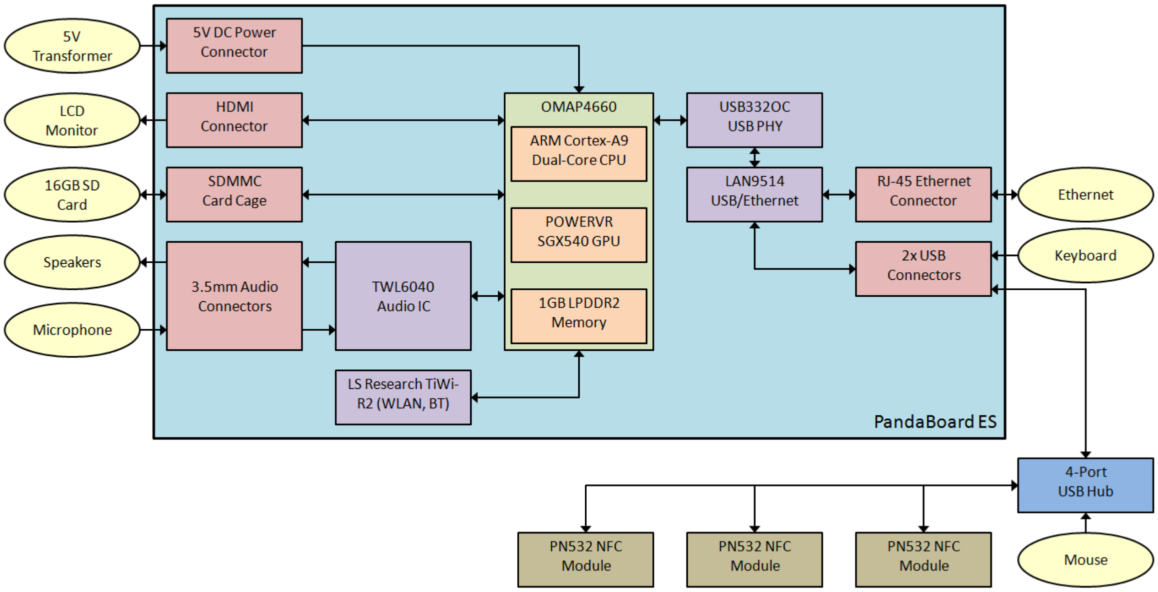


Figure 5.1: A block diagram of the NFC testing platform detailing its primary components. Unused PandaBoard ES functions are not shown in this Figure. The PN532 modules each use a USB to UART adapter cable.

ports, an a full-size Secure Digital (SD) card reader that allows SD cards to act as the system disk.

- *Adafruit PN532*: The three rectangular modules atop the Teddy Grahams box in Figure 5.2 are Adafruit PN532 Breakout Boards [85]. The PN532 is a popular NFC chip that supports reading and writing to RFID cards, communicating with other NFC devices in the active peer-to-peer mode, and card emulation for passive-mode communication. A USB to UART cable [86] connects each PN532 board to the PandaBoard ES. Each PN532 board and USB cable combination was US$60 at the time of this writing.

- *Supporting Elements*: In addition to the core elements, the testing platform utilizes a USB hub to expand the number of ports available on the PandaBoard ES and an Ethernet cable to provide network access for remote logins. The system disk is a 16 GB class 10 SD card from SanDisk.

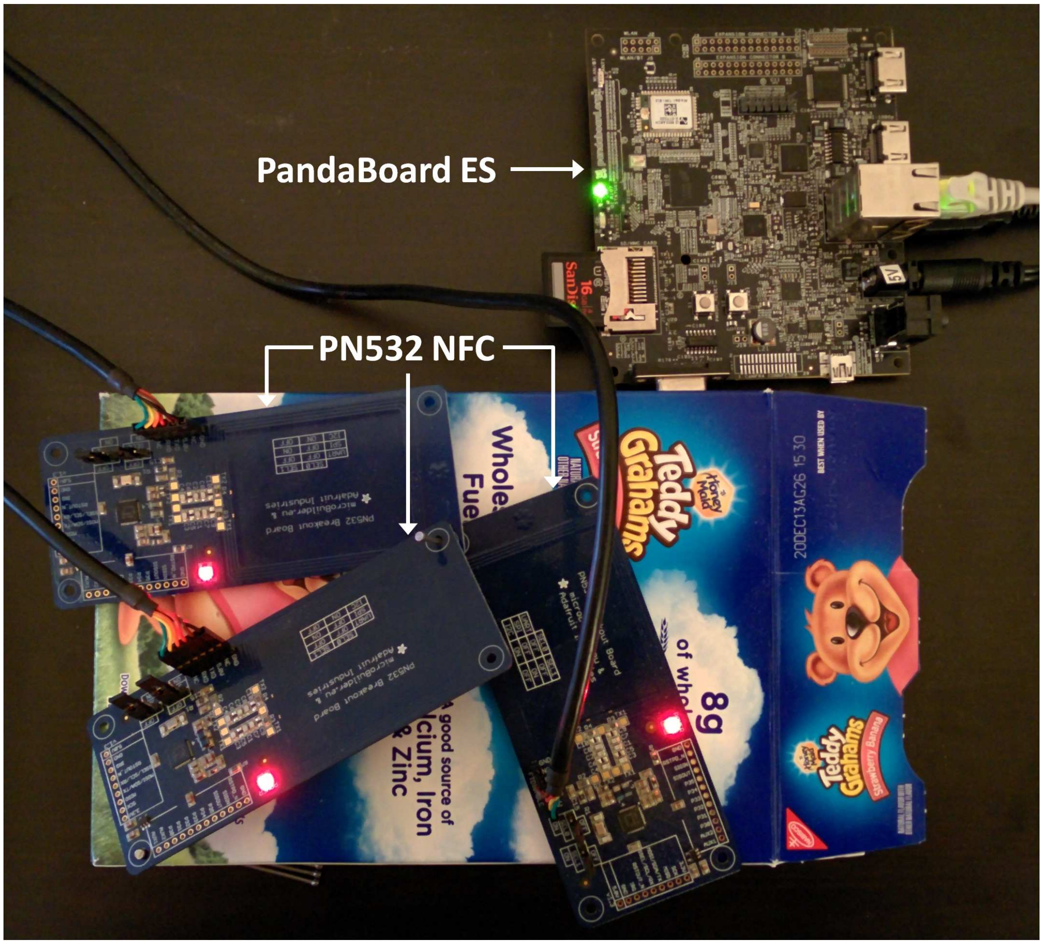


Figure 5.2: Photograph of the NFC testing platform. The 5V DC transformer and basic USB hub are not shown in this Figure. The Teddy Grahams box and a few nails hold the very lightweight NFC modules in place.

Both the PandaBoard ES and the Adafruit PN532 NFC module are open-source hardware, which means that the schematics and bills of materials are available for free and without a license. Figure 5.1 shows a block diagram of the major components of both modules and where they fit into the overall testing platform.

The testing platform supports two primary configurations. In the first, the Pandaboard ES is connected to a local network using an Ethernet cable and the onboard RJ-45 connector. This configuration allows the user to control the system remotely via the ssh program in Linux or an application like PuTTY in Windows. If Ethernet is not available, then the

Pandaboard ES can connect to the local network via WiFi or Bluetooth by utilizing the LS Research TiWi-R2 device. However, using this device seems to produce instability in the system, often resulting in kernel panics and system freezes. Thus, the Ethernet connection is preferable.

In the second configuration, the user can connect a keyboard, a mouse, and a monitor directly to the Pandaboard ES, negating the need for network support. The monitor must have an HDMI connector because the Pandaboard ES's DVI connector is not fully functional at the time of this writing. The keyboard and mouse should be connected via USB. Since the Pandaboard ES has only two USB ports, a USB hub is necessary to utilize the keyboard, mouse, and three NFC devices simultaneously. The prefered connection scheme uses a four-port USB hub to connect the mouse and three NFC devices while the keyboard is connected directly to the board, as shown in Figure 5.1.

Other hardware was considered for inclusion in the NFC testing platform. Compared to the Pandaboard ES, the Raspberry Pi [87] has less memory at only 512MB, has a much less capable processer, and lacks the Pandaboard's WiFi and Bluetooth capabilities. In addition, the Raspberry Pi is less open than the Pandaboard ES, lacking public PCB design files. Finally, the CPU used on the Raspberry Pi is no longer supported by many popular Linux distributions. Despite these limitations, the Raspberry Pi could nevertheless serve as a decent heart for a NFC test platform. It carries a much lower price than the PandaBoard ES, has smaller physical dimensions, and has a large community of users.

Instead of a using a combination of the PandaBoard ES and the PN532 NFC module, one might use a modern smartphone. Models like the LG Nexus 5 contain more powerful hardware than the PandaBoard ES and use newer NFC chips. However, such devices tend to carry high costs and are much less open than the PandaBoard ES. Additionally, while programming an application for the PandaBoard ES is essentially no different than programming an application for a typical personal computer, programming on a smartphone requires the programmer to learn a new system of tools and restrictions.

Future iterations of the NFC testing platform might include more modern NFC devices that support the NFC-SEC protocols, such as the PN533 [88]. At the time of this writing, no open-source hardware devices carry such a chip. A module similar to the PN532 from Adafruit but instead carrying a PN533 chip would certainly improve the NFC testing platform.

5.2 Software

The operating system for the NFC testing platform is Ubuntu 12.04 LTS (Precise Pangolin) [89], a free, open-source Linux distribution. Ubuntu 12.04 is recommended by Texas Instruments for the PandaBoard ES and is available as a pre-configured image. In addition, Ubuntu 12.04 was the development platform for Texas Instruments engineers and thus provides packages to install additional drivers and utilities for the PandaBoard ES. The operating system is stored on the 16 GB SanDisk SD card.

While the NFC testing platform uses Ubuntu, the PandaBoard ES is supported by numerous other operating systems, including Fedora and Gentoo Linux. There are also Android builds available for the PandaBoard ES, which more closely mirror the software found on most smartphones. None of these alternative operating systems are recommended by Texas Instruments, but all of them support the hardware just as well.

On top of Ubuntu, a free, open-source library called *libnfc* [90] provides low-level drivers and utilities for interacting with the PN532 device as well as with many other NFC devices. The software described in Section 6.2 was built against version 1.7rc7 of libnfc as this was the latest version available at the time of the experiments.

Future versions of the NFC testing platform might incorporate other free, open-source utilities such as *libfreefare* [90], which provides functions for working with MIFARE tags, and any of the numerous libraries available for reading and writing NDEF records. Newer, more stable versions of Ubuntu or another operating system would also improve the NFC testing platform.

5.3 Implementation

In order to recreate the test platform, the user must first install Ubuntu 12.04 to a SD card. Insert the card, then connect a monitor, keyboard, and mouse. Power the Pandaboard

ES to boot the system. For a wired Ethernet connection, simply connect a standard Cat5 cable. The included Network Manager software can configure wireless networks.

Next, update the system. The following commands in will update any pre-installed software, add the TI repository for Pandaboard, and perform a full system upgrade. Then, they install the Pandaboard ES software and firmware from the Texas Instruments repository and configure the system to use it.

```
sudo sed --in-place=.bak -e ’s/\ˆ# \(deb.*\)/\1/’ /etc/apt/sources.list
sudo apt-get update

sudo apt-get install python-software-properties
sudo add-apt-repository ppa:tiomap-dev/release
sudo apt-get update
sudo apt-get dist-upgrade

sudo apt-get install ubuntu-omap4-extras
sudo apt-get install --reinstall pvr-omap4-dkms
alsaucm -c PandaES set _verb HiFi
sudo flash-kernel --update-bootloader
```

Reboot the system. These next commands install some libraries and programs that libnfc depends on.

```
sudo apt-get install libusb-dev libpcsclite-dev
sudo apt-get install libusb-0.1-4 libpcsclite1 libccid pcscd
sudo apt-get install subversion
sudo apt-get install debhelper dh-autoreconf libtool
sudo apt-get install dpkg-dev
```

Finally, install libnfc according to the instructions found on the libnfc website [90]. Once that is finished, run the following commands to remove any unneeded software and allow you to use libnfc and the Pandaboard ES properly. Remember to replace “username” with your actual username!

```
sudo apt-get autoremove
useradd -a -G dialout username
```

With at least one PN532 connection via USB cable, use the `nfc-list` command. If no devices are found, then something went wrong. Otherwise, everything is OK!

Mostly, the system behaved as expected. However, the WiFi module was quite flaky and often caused the system to lock up. Using a wired Ethernet connection produced a much more stable system. Additionally, logging into the system remotely via SSH improved stability over using the Ubuntu GUI locally. Even with the above changes, the system would still rarely lock up. Advisors in the #pandaboard IRC channel on the Freenode network attributed these freezes to the SD card. While the SD card is necessary to boot the system, using an attached USB drive for everything else might improve overall system stability.

5.4 Chapter Summary

The NFC testing platform allows researchers to test NFC hardware and software implementations for protocol correctness, security flaws, efficiency, and features. It is comprised entirely of commercially-available, off-the-shelf, open-source hardware and free, open-source software. This chapter described the many components that make up the NFC testing platform and explained why those components were chosen. Additionally, this chapter provided implementation details and noted limitations of the system.

Chapter 6

An Analysis of Double Target Trouble

Section 2.3.2.1 describes a single-device detection protocol to ensure that a NFC device communicates with only one other NFC device. This chapter details an experiment that shows what happens when this protocol fails.

6.1 The Problem

Standard NFC transactions are point-to-point and only involve two devices: the Initiator and the Target. When an Initiator wishes to communicate with a Target device, it first performs the single-device detection algorithms described in Section 2.3.2.1. There are a few reasons for this behavior.

First, all NFC devices communicate on the same 13.56 MHz frequency band. Thus, multiple simultaneous transmissions in close proximity will cause interference. If more than one Target device responded to the Initiator's commands, then the Initiator might not be able to read any responses at all. By selecting only one Target, the Initiator ensures that only one standards-compliant NFC device is transmitting at any given time. Secondly, some NFC transactions contain sensitive information. For instance, NFC devices can store payment information, medical information, or access credentials. If the Initiator is not careful to select the correct Target, then malicious devices could spoof this information. Finally, the Initiator might wish to obtain information from a specific device with a known identifier. In this case, the Initiator simply needs to select the correct Target from all possible Target devices in range. The single-device detection algorithms can do this.

What happens if the single-device detection algorithm does not function as expected?

6.2 Proposed Experiment

In order to conduct this experiment, three PN532 NFC devices are connected to the PandaBoard ES, as shown in Figure 5.2. Note that the three loop antennas are all touching and that one NFC device is sandwiched between the other two. In this configuration, the Initiator device is in the center and is flanked by the two Target devices.

Figure 6.1 illustrates the general testing procedure for each iteration of the Double Target Trouble experiment. Each of three NFC devices was assigned an alias. Alice is the Initiator device; Bob and Eve are the Target devices. First, the program configures the two Target devices so that they are idly and waiting for an Initiator to communicate. Then, it initializes Alice to look for a Target device. When she finds one, she transmits the message, “Hello! I’m Alice!”. If either Target receives that message, then it responds with, “Hello to you, too!”. If Alice receives a response, then she sends the message, “Who are you?”. If Bob receives this second message from Alice, then he responds with, “I’m Bob!”. Likewise, if Eve receives the second message, then she responds with, “I’m Eve!”. Not shown in Figure 6.1 is a 5 second delay between each iteration of the test to allow all three devices time to disconnect from libnfc.

If the single-device detection algorithm is working correctly, then Alice should receive a response to each of her messages from Bob *or* Eve, but not both. Likewise, only Bob *or* Eve should detect that they have paired with Alice. If Alice fails to receive a message, or if she receives a message from an unknown sender, then a data collision has occurred. If Bob and Eve do not agree on who responded to Alice, then the target selection process has failed.

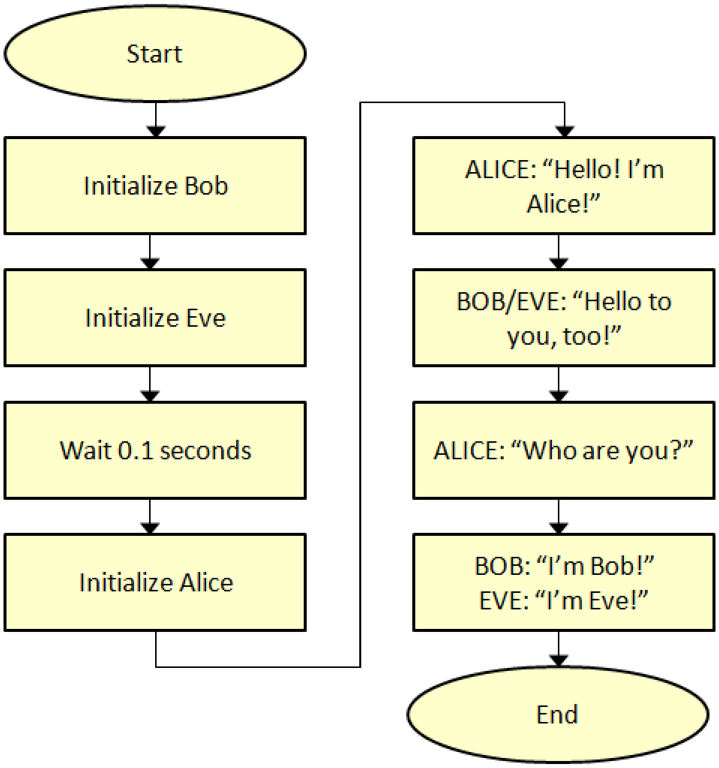


Figure 6.1: Flowchart of the Double Target Trouble experiment. This process was run 1,000 times for each system configuration.

6.3 Experimental Results and Analysis

As a control, one thousand iterations of the test are executed with only Alice and Bob connected to the system. Then, one thousand iterations of the test are executed with only Alice and Eve connected to the system. These tests were run with a data rate of 424 Kbps using the active transmission mode and with the device antennas touching. Figure 6.2 shows the results of the control tests.

Each bar represents the last status that the device returned before disconnecting. Thus, a status of "Init OK" indicates that the device initialized properly, but did not transmit any messages. Unfortunately, one of the PN532 modules has a defect in the UART connector. In order to ensure that both Targets are equal, the defective module is Alice. Figure 6.2 shows that approximately 0.1% of tests fail because Alice was not initialized. The other

99.9% of tests worked as expected with Alice received both responses from her intended Target.

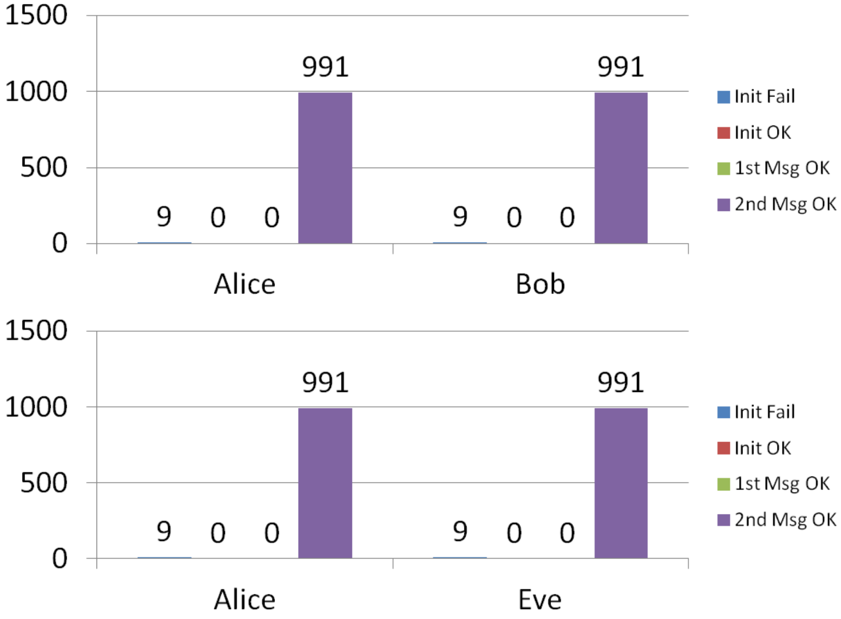


Figure 6.2: DTT control test. Alice has approximately a 0.1% failure chance due to a defect in the UART connector. Each test was conducted at a data rate of 424 Kbps active with the NFC boards touching.

For the first set of real tests, all three loop antennas were connected together with Alice's antenna in the middle of the stack such that the distance between Alice and Bob is equal to the distance between Alice and Eve. The data rate was set to 424 Kbps and configured the boards were configured to use the active transmission mode. One thousand iterations of the test were executed in this configuration.

As Figure 6.3 shows, the three devices do not agree on what happened. First, consider Alice. Alice failed to initialize 0.1% of the time, as expected from the control tests. In 20% of the tests, she initialized properly and found a Target device, but could not receive any messages. The most likely cause of this behavior is a collision during the transmission of the first message. Approximately 18% of tests ended with one message pair transmitted successfully, but not the second pair. This might happen when both Targets transmit simultaneously. The first message from each Target is the same, but the second differs.

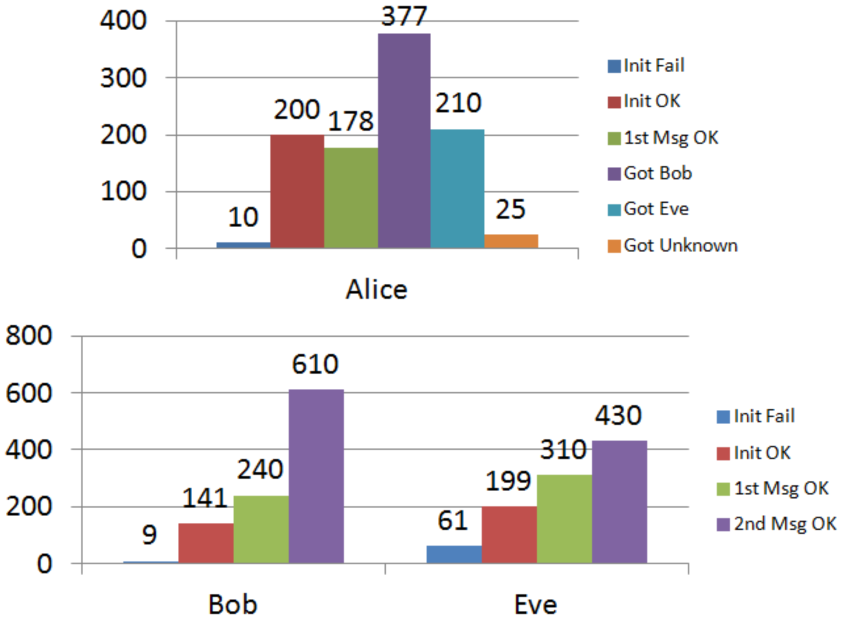


Figure 6.3: DTT test at 424 Kbps active with Bob, Eve, and Alice touching.

Thus, a collision during transmission of the second message would produce this result. Alice got two messages from Bob 377 times and two messages from Eve 210 times. Finally, she received a message from an unknown sender 25 times. This occurs when there is a data collision in the second message, but not in the message headers. So, Alice receives the second message, but the send is not “Bob” or “Eve”.

However, Bob and Eve do not agree with these results. When a Target reports the “Init Fail” status, it indicates that the Target was not selected by an Initiator device during the test. Bob was not selected in 0.1% of tests, likely because Alice failed to initialize. In 14% of cases, Bob was selected, but never received a message from Alice, and in 240 tests, he received one message from Alice, but not the second. Bob believes that he successfully transmitted both messages to Alice 610 times. Eve was less successful. She was not selected 61 times, received no messages in approximately 20% of the tests, received only one message in 30% of the tests, and was only able to receive both messages in 43% of the tests. Both Target devices believe that they were successful 150% to 200% more often than they actually

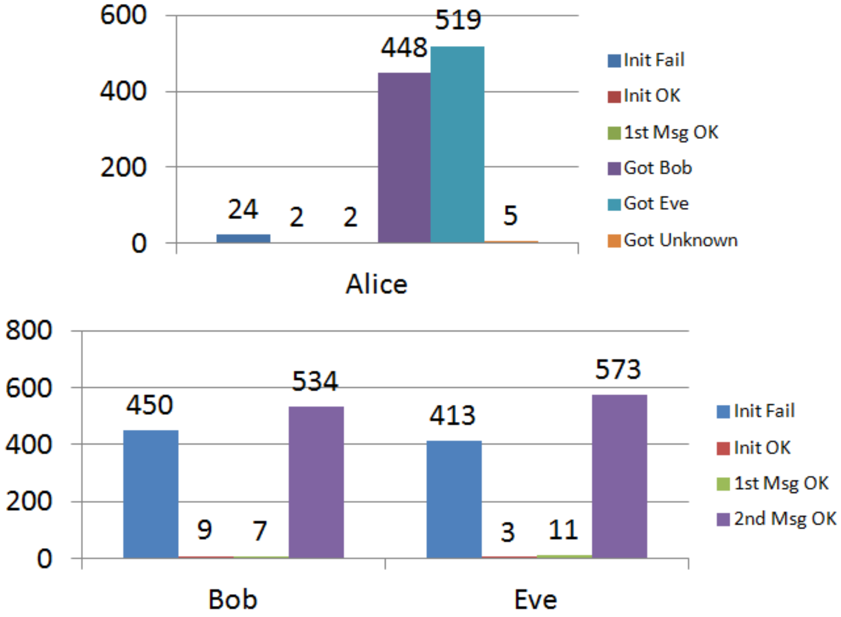


Figure 6.4: DTT test at 424 Kbps passive with Bob, Eve, and Alice touching.

were.

The second set of tests is identical to the first, except that the devices operate in passive mode and thus use a different single-device detection algorithm. This test will determine if the problem lies in the single-device detection algorithm or elsewhere in the system. Figure 6.4 shows the results of running one thousand iterations of this test.

First, notice that Alice failed to initialize more often than the control would suggest. However, these failures still only account for 0.24% of the tests. Second, the results of this test are much different than the results of the first. Alice received two messages from either Bob or Eve in 96.7% of attempts. Unfortunately, the Target devices still can't agree on who was successful. Bob thought that he was successful 53.4% of the time when in fact he only succeeded in 44.8% of attempts. Eve was similarly optimistic, believing that she succeeded about 5% more often than she did.

The third set of tests is identical to the first, except that the data rate is set to 106 Kbps instead of 424 Kbps. Since the devices are still in active mode, the single-device detection

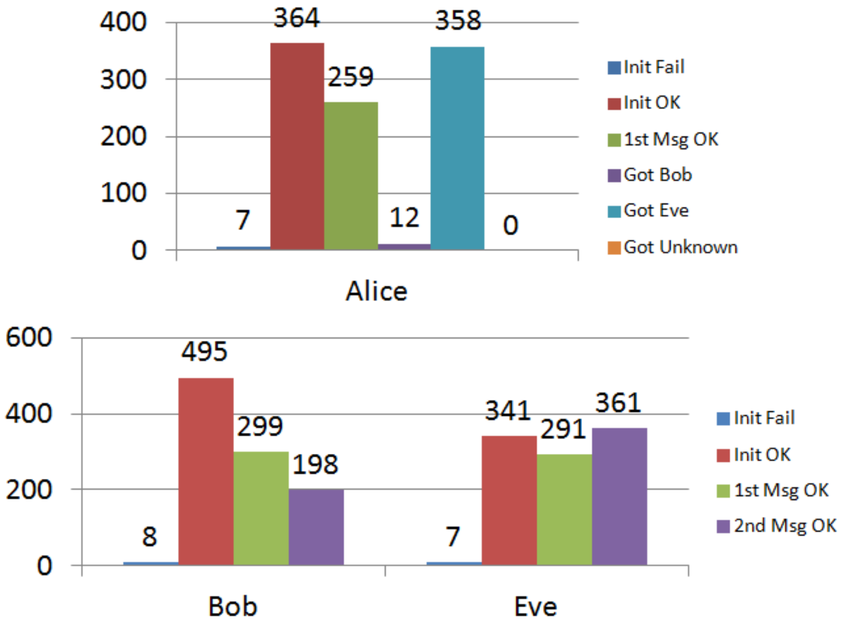


Figure 6.5: DTT test at 106 Kbps active with Bob, Eve, and Alice touching.

algorithm is the same as the first. Thus, this test set tests whether the transmission speed affects the active mode single-device detection algorithm. Figure 6.5 shows the results of one thousand iterations of this test.

The majority of these attempts (about 64%) ended with zero or one message pairs successfully transmitted as a result of data collisions. Both Bob and Eve see 30% of the iterations failing after the first message pair and Alice almost agrees with this result. The disparity is caused by collisions during the transmission of the first response headers. For the second message pair, Eve was far more successful than Bob. This is because Eve was selected as a Target more often than Bob. Notice that Eve and Alice very nearly agree on the number of successful second responses. However, Bob's viewpoint is highly distorted, showing a 20% success rate when the actual rate was 0.12%. Bob sent his second response and called the test a success whenever he got a second message from Alice. Unfortunately for him, Eve usually was the selected Target and so Alice received her messages instead.

In order to determine if distance changes the results, three more sets of tests were

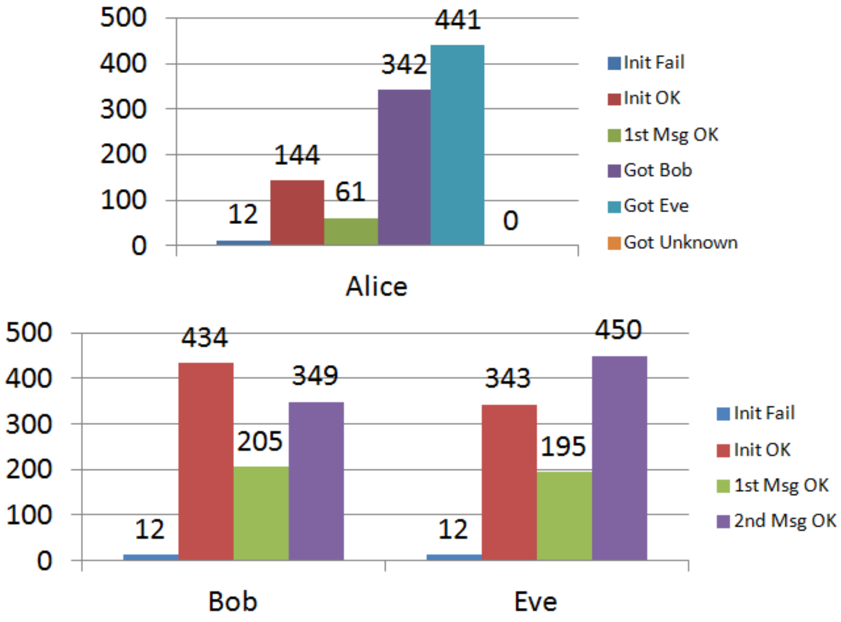


Figure 6.6: DTT test at 424 Kbps active with Eve 4 cm from Alice and Bob touching Alice.

executed that were identical to the first three except that Eve was positioned 4 cm away from Alice while Bob remained in direct contact with Alice. For these particular NFC devices, 4 cm was the maximum observed distance in which 100% of control tests were successful.

Figure 6.6 shows the results of the fourth test. Notice that the "Init OK" percentages are very high for both Bob and Eve. Bob was not selected in 43% of iterations, allowing Eve to send her messages without any problems. Similarly, Eve was not selected in 34% of trials, which allowed Bob to send his messages successfully. Alice's success numbers very nearly match those of Bob and Eve. Each Target only differs from Alice by 0.8% 0.9%. These results imply that stationing one Target further from the Initiator improves the single-device detection algorithm in libnfc.

The fifth test was the most successful, as shown in Figure 6.7. Alice and Bob agree entirely on the outcome. Bob's success rate in sending both messages was 99.4%! However, Eve is still a problem. She sees one or two successful messages in the same 99.4% of iterations when in fact she did not transmit any messages successfully. Devices have as shorter range

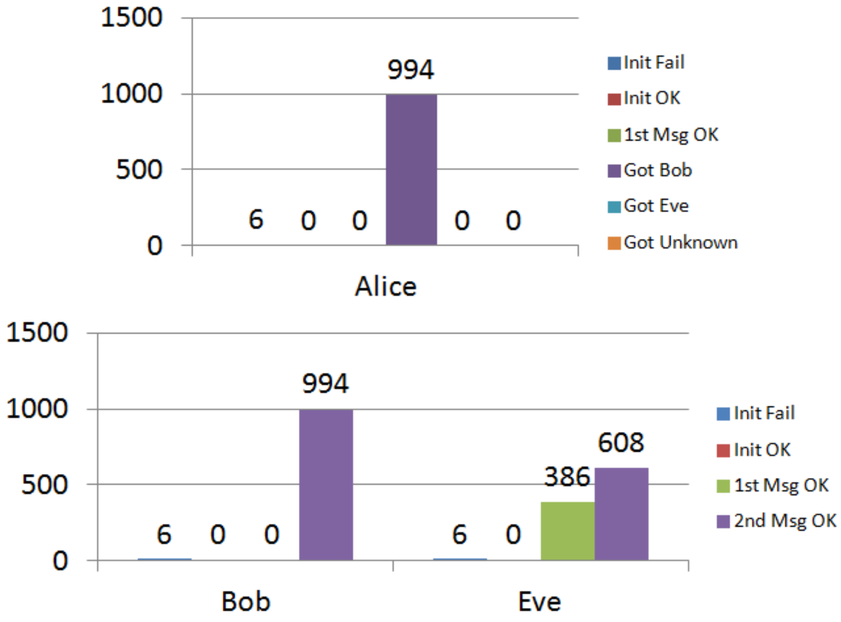


Figure 6.7: DTT test at 424 Kbps passive with Eve 4 cm from Alice and Bob touching Alice.

in passive mode since passive Targets do not generate their own RF fields. While Eve had no trouble modulating Alice's field in the control test, her power is not strong enough to cause problems for Bob, who is closer to Alice. Nevertheless, Eve receives Alice's messages, implying that she believes herself to have been selected by Alice when she should not have been.

The final test set is summarized in Figure 6.8. As with the other active tests, the single-device detection algorithm performed poorly. In 27% of trials, Alice could not select a Target. In another 20%, either Bob or Eve sent only a single messages, having been selected when they should not have been. Despite this, the numbers of successful transmissions very nearly match for Alice and either Target device.

6.4 Security Implications

If an Initiator cannot select a single Target with which to communicate, then the NFC protocol breaks down. Table 6.1 summarizes the results presented in the previous section.

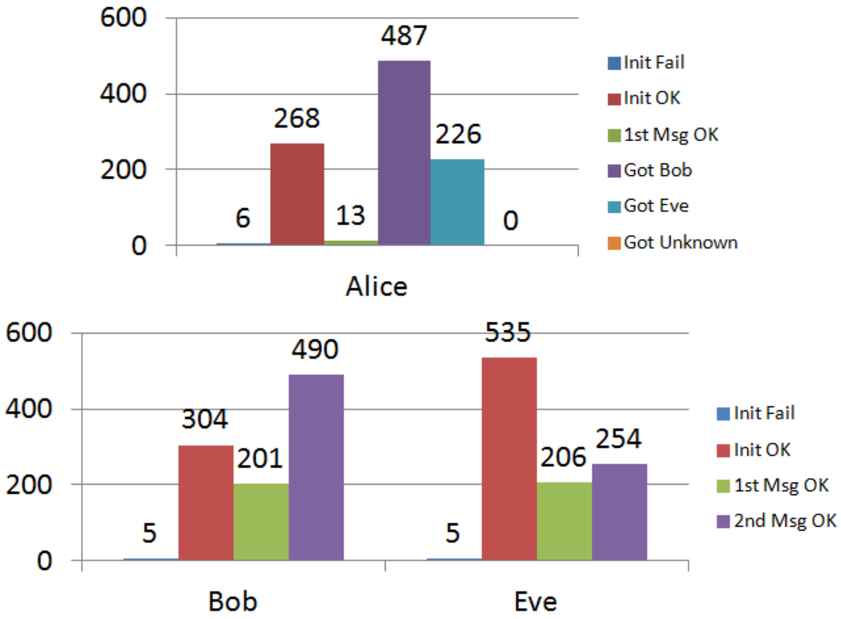


Figure 6.8: DTT test at 106 Kbps active with Eve 4 cm from Alice and Bob touching Alice.

Clearly, something is wrong. The active tests did not go well. In the majority of active tests, Alice was not able to communicate properly with Bob or Eve. Passive tests look better in Table 6.1, but from Bob and Eve's perspectives, we know that even the passive tests produces many disagreements among the three devices. Perhaps the fault lies with the PN532 device. Maybe libnfc is to blame. Regardless, a bad actor could intentionally write his library or design his device to behave in this manner. What sort of damage could he do?

Malicious Target devices could cause trouble in a number of ways. First, they could eavesdrop on sensitive data. Not all NFC communications are encrypted and not all NFC devices support the NFC-SEC protocol described in Section 3.4. Indeed, the PN532 devices used in these experiments do not support the NFC-SEC protocol. There are some alternatives. The PN532 supports a secure access module (SAM). A SAM can provide encryption and key management services for the NFC device. One example of a SAM is the subscriber identity module (SIM) present in many mobile phones. Similarly, the NFC device might rely on another system such as the ARM processor in the PandaBoard to provide encryp-

Table 6.1: Double Target Trouble results from Alice's perspective.

Test	Success	Collision	Init Fail
Control	991	0	9
424K, Active, 0cm	587	403	10
424K, Passive, 0cm	968	9	24
106K, Active, 0cm	370	623	7
424K, Active, 4cm	783	205	12
424K, Passive, 4cm	994	0	6
106K, Active, 4cm	713	281	6

tion services. However, both solutions add another element to the system that could be compromised through security flaws or side-channel attacks.

Secondly, a malicious Target device could spoof data. Consider a passive RFID tag used for advertising purposes. Perhaps a customer with a NFC-enabled mobile phone is meant to read the tag, which then directs her to a website. If another RFID tag is placed in close proximity, but hidden from the customer's view, then she might inadvertently read the wrong tag and find herself on a different website. This website might be offensive or it might contain a computer virus. Similarly, one might hide a Target device near a payment terminal. If a customer attempts to pay with his NFC-enabled mobile phone, then the malicious Target might instead respond to the card reader's request for information. In this way, the payment could be charged to the wrong account or it could be blocked entirely.

Finally, a malicious Target might perform other denial of service attacks. Since all NFC devices communicate on the same frequency band, a Target could ignore the NFC protocol and transmit whenever another Target attempts to do the same. As these experiments show, the Initiator might never receive the message and the the real Target device might be none the wiser. Using this technique, a bad Target device could block payments, access to restricted areas that use NFC or RFID tags for credentials, advertising, and peer-to-peer NFC communications.

6.5 Chapter Summary

This chapter presented an experiment that showed what happens when NFC Target devices do not follow the NFC protocol. Whether by accident or intentionally, a bad Target device could eavesdrop on sensitive data, spoof data, and deny service to legitimate devices. While encryption can alleviate the first problem and more advanced security services can somewhat alleviate the second, neither is effective against the third type of attack. Further, not all devices are suitable for encryption. For instance, one would not wish to forget his private key when accessing critical medical sensor information.

Chapter 7

NFC-SEC Proof of Security

The NFC-SEC protocol [53][54] described in Sections 3.4 - 3.5 offers one solution to some of the problems described in Chapters 4 and 6. This chapter examines the security of the NFC-SEC-1 [54] version of that protocol using a system called Protocol Composition Logic.

7.1 Protocol Composition Logic

Protocol Composition Logic (PCL) is a formal logic for stating and proving security properties of network protocols [92][93]. PCL breaks a protocol down into *roles*, such as "client" and "server" or "initiator" and "target". A *thread* is a *principal*, such as Alice or Bob, executing one role of a protocol. Each role contains zero or more *basic sequences*, each of which is composed of one or more actions performed by the principal. If a basic sequence contains a `receive` action, then that action must be the first element of the sequence.

In order to reason about protocols, PCL uses assertions of the form $\varphi[\mathtt{actseq}]_{\mathtt{T}}\psi$, which states that if the thread `T` is in state φ and performs the actions contains in `actseq`, then ψ is true in the resulting state. Importantly, the actions contained in `actseq` are all performed as part of thead `T`'s role and not by any other party. PCL does not require explicit reasoning about the actions of attackers or other third parties.

Parts of this Chapter were submitted for publication to Wiley Security and Communication Networks [91].

The preconditions φ and postconditions ψ can be simple boolean expressions, such as `true` and `false`, or they can contain one or more action predicates. Some action predicates include `Send(T,msg)`, which says that thread `T` sent the message `msg`, `Has(T,msg)`, which says that thread `T` either created or otherwise received `msg` and that `msg` is not hidden from `T` by encryption, and `Honest(Pname)`, which simply says that the principal with name `Pname` is honest. An honest principal is one who executes her role as prescribed by the protocol and who does not share any secret information with other parties. For example, if Alice shares her private key, then `Honest(Alice)` would be `false`. Additionally, PCL uses standard predicate logic and modal operators to connect predicates and actions. For a complete set of basic action predicates and operators, please see [92].

The first step of analyzing a protocol with PCL is to explicitly state each role in the procotol. When doing so, there are some rules to consider:

- A role must not have any free variables. Keys must be constants, parameters passed to the role at startup, or derived from received messages. This rule applies to non-key variables as well, especially principal names.

- Each variable must be assigned only once and each variable must not be used until it has been assigned. To facilitate this rule, roles must be described without loops.

- If a key is confidential, then it cannot be assigned to variable. That is, if a key `K` is confidential, then the action `var := K` would be illegal. Neither can `K` be an argument to another function unless that function requires an argument of type `key`. For example, the `enc` function is the asymetric encryption function. Its signature is of the form `location` × `message` × `asym_enc_key`. Thus, `var := enc msg, K` would be a legal action because `K` is of type `asym_enc_key`, a subtype of `key`.

- Variables are local to threads. That is, they may only be read from within a role assigned to a specific thread.

Protocols are written with a blank line to separate basic sequences for readability. Components of complex data types are written with record notation. For instance, `T.pname`

Algorithm 7.1: PCL Algorithm for NFC-SEC-1 Initiator.

```
Initiator(A,B : NFCID3) {
    n_A := newnonce;
    act_req_A := <pk(A),n_A>;
    send act_req_A;

    act_res_A := receive;
    <pk_B,n_B> := act_res_A;
    assert: ValidECP(pk_B, P192);
    <Px,Py> := dk(A) * pk_B;
    z_sse := Px;
    keyseed := se(z_sse, <n_A,n_B>);
    mk_sse := se(<n_A,n_B,A,B,01>, keyseed);
    mac_tag_A := se(<03,A,B,pk(A),pk_B>, mk_sse);
    send mac_tag_A;

    mac_tag_B := receive;
    mac_tag_vA := se(<02,A,B,pk(A),pk_B>, mk_sse);
    assert: mac_tag_vA = mac_tag_B;
    Z := mk_sse;
}
```

refers to the `pname` (principal name) of thread `T` (*e.g.* Alice or Bob). Finally, a vector is denoted with angular brackets (< and >).

7.2 NFC-SEC-1 SSE Algorithm

Algorithm 7.1 explicitly states the NFC-SEC-1 protocol from the perspective of the Initiator role. The Initiator requires two NFCID3 parameters, called *A* and *B*. As previously, A and B will be Alice and Bob, respectively.

In the first basic sequence, Alice generates a new nonce and sends it, along with her public key, *pk(A)*, as an ACQ_REQ message. In the second basic sequence, she receives an ACT_RES message from (presumably) Bob containing his public key and his (presumably)

Algorithm 7.2: PCL Algorithm for NFC-SEC-1 Target.

```
Target(B,A : NFCID3) {
    act_req_B := receive;
    n_B := newnonce;
    act_res_B := <pk(B),n_B>;
    send act_res_B;
    <pk_A,n_A> := act_req_B;
    assert: ValidECP(pk_A, P192);
    <Px,Py> := dk(B) * pk_A;
    z_sse := Px;
    keyseed := se(z_sse, <n_A,n_B>);
    mk_sse := se(<n_A,n_B,A,B,01>, keyseed);

    mac_tag_A := receive;
    mac_tag_vB := se(<03,A,B,pk_A,pk(B)>, mk_sse);
    assert: mac_tag_vB = mac_tag_A;
    mac_tag_B := se(<02,A,B,pk_A,pk(B)>, mk_sse);
    send mac_tag_B;
    Z := mk_sse;
}
```

newly generated nonce. She asserts that Bob's public key is valid on the P-192 elliptic curve [56]. Then, she calculates the first shared secret using her private key, *dk(A)*, Bob's public key, and the ECSVDP-DH primitive [94]. Alice has now completed the key agreement protocol with (presumably) Bob.

Next, Alice uses the first shared secret, *z_sse*, to derive the master key for the Shared Secret Service (SSE), *mk_sse*. In this Algorithm, the `se` function stands for the proper AES encryption algorithm, as specified in the NFC-SEC-1 standard [54]. At this point, Alice has completed the key derivation protocol. To finish the second basic sequence, Alice generates a MAC tag using *mk_sse* and sends it to Bob as a VFY_REQ message.

In the final basic sequence, Alice receives a VFY_RES message from Bob containing his MAC tag. She generates the expected value for Bob's MAC tag and compares it with the one that she received. If they match, then Alice has completed the key verification protocol with Bob.

Algorithm 7.2 states the same NFC-SEC-1 protocol from the Target's perspective. When Bob receives an ACT_REQ, he generates a new nonce and sends it, along with his public key, as an ACT_RES message. Then, he verifies that the received message contains a valid public key and, if so, calculates the first shared secret using his private key, *dk(B)*. Bob has thus completed the key agreement sequence. If Alice is an honest player, then Bob's *z_sse* will match Alice's. Bob then completes the key derivation protocol for SSE, resulting in *mk_sse*.

In the second basic sequence, Bob receives a VFY_REQ message, which should contain Alice's MAC tag. Bob generates the expected MAC tag value and compares it with the one that he received. If they match, then Bob has completed the key verification protocol and has established a shared key with Alice.

7.3 The PCL Proof System

Protocol Composition Logic provides a framework for proving authentication and secrecy properties for network protocols. Proofs are written as a sequence of statements in the form $\varphi[\mathtt{actseq}]_{\mathrm{T}}\psi$ in which numerous axioms and inference rules connect the statements together. Generally, if $\varphi[\mathtt{actseq}]_{\mathrm{T}}\psi$ holds and one wants to prove that $\varphi[\mathtt{actseq}]_{\mathrm{T}}\psi\prime$ holds, then it suffices to show that $\psi \Rightarrow \psi\prime$. The basic axioms are divided into categories. Some of the more important ones are as follows:

- *AA0*: Axioms that infer the status of a run's storage based on action sequences performed by threads. For example, the following axiom states that if a thread performs the action $\mathtt{assert} : \mathtt{msg}_1 = \mathtt{msg}_2$, then $\mathtt{msg}_1$ is equal to $\mathtt{msg}_2$.

  $$true[\mathtt{actseq}; \mathtt{assert} : \mathtt{msg}_1 = \mathtt{msg}_2; \mathtt{actseq}\prime]_{\mathrm{T}}\mathtt{Sto}(\mathtt{T}, \mathtt{msg}_1) = \mathtt{Sto}(\mathtt{T}, \mathtt{msg}_2)$$

- *AA1*: If a thread performs an action, then the predicate asserting that the action has taken place evaluates to true. For example, the following axion says that if a thread performs the `newnonce` action, then that thread has in fact performed that action.

  $$true[\mathtt{actseq}; \mathtt{loc} := \mathtt{newnonce}; \mathtt{actseq}\prime]_{\mathrm{T}}\mathtt{NewNonce}(\mathtt{T}, \mathtt{Sto}(\mathtt{T}, \mathtt{loc}))$$

- *AA2*: If a thread has not performed any actions, then a predicate asserting that a thread did perform an action evaluates to false. For example, the following axiom says that if a thread has not performed any actions, then that thread did not perform a `send` action.

  $\mathtt{Start(T)}[\,]_{\mathtt{T}}\neg\mathtt{Send(T,msg)}$

- *AA3*: Axioms used to prove that certain messages have not been sent by a thread. For example, the following axiom states that if a message has not been sent by a thread and the thread performs any action sequence not containing a `send` action, then the message still has not been sent by that thread.

  $\forall\mathtt{actseq}$ not containing a `send` action : $\neg\mathtt{Send(T,msg)}[\mathtt{actseq}]_{\mathtt{T}}\neg\mathtt{Send(T,msg)}$

- *AN1*, *AN2*, *AN3*, *AN4*: Axioms concerning nonces. These three axioms state that the thread generating a given nonce is unique, that only the thread generating a nonce has that nonce just after generation, that a nonce is *fresh* just after generation, and that a thread only has a fresh nonce if it generated that nonce. A nonce is fresh when it has not been sent as part of any message.

- *KEY*: Axioms concerning the possession and secrecy of keys. These axioms depend on the setup assumptions of the protocol in question. For example, if all threads have access to their own signing keys and all threads are *honest*, then a thread with access to `sk(Pname)` must be the thread assigned to the principal with name `Pname`.

  $\mathtt{Has(T,sk(Pname))}\wedge\mathtt{Honest(Pname)}\Rightarrow\mathtt{T.pname}=\mathtt{Pname}$

- *HAS*: These axioms describe the `Has` predicate. For example, if a thread receives a message, then that thread has that message.

  $\mathtt{Receive(T,msg)}\Rightarrow\mathtt{Has(T,msg)}$

- *SEC*: If a protocol includes private keys in the setup assumptions, then only the principal that owns a private key can decrypt with it, providing that that principal is honest.

- *VER*: Similarly, only the principal owning a signing key can sign messages with that key, providing that that principal is honest.

- *P1*: The predicates Has, Sign, NewNonce, and FirstSend are preserved across all action sequences.

- *P2*: If a message is fresh, then it it still fresh after an action sequence that does not contain a send action. Similarly, the freshness of a message is preserved after an action sequence in which any send actions do not send a message containing the one in question.

- *FS1*: If a nonce is fresh, then it is "sent first" when the first send action containing that nonce occurs. That is,

  $$\begin{aligned}&\mathtt{Fresh}(\mathtt{T},\mathtt{msg}_1)[\mathtt{send}\ \mathtt{msg}_2]_\mathtt{T}(\mathtt{msg}_1 \subseteq \mathtt{Sto}(\mathtt{T},\mathtt{msg}_2) \Rightarrow\\ &\quad \mathtt{NewNonce}(\mathtt{T},\mathtt{msg}_1) \wedge \mathtt{FirstSend}(\mathtt{T},\mathtt{msg}_1,\mathtt{Sto}(\mathtt{T},\mathtt{msg}_2)))\end{aligned}$$

- *FS2*: If a thead first sent a nonce as part of a message and another thread receives a message containing that nonce, then the send action occured before the receive action.

The axioms listed above are meant to be illustrative and are by no means comprehensive. For a complete list of basic axioms, and for a list of other rules, please see [92].

In order to aid with the proofs in Section 7.4, we define *Axiom FS3*: If a thread first sent a message $\mathtt{msg}_1$ as part of $\mathtt{msg}_2$ and another thread received a message $\mathtt{msg}_3$ containing $\mathtt{msg}_1$, then the receive action occured after the send action. This axiom follows from FS2 defined in [92].

$$\begin{aligned}&((\mathtt{Fresh}(\mathtt{T}_1,\mathtt{msg}_1) \wedge \mathtt{FirstSend}(\mathtt{T}_1,\mathtt{msg}_1,\mathtt{msg}_2))\\ &\quad \wedge(\mathtt{T}_1 \neq \mathtt{T}_2) \wedge (\mathtt{msg}_1 \subseteq \mathtt{msg}_3) \wedge \mathtt{Receive}(\mathtt{T}_2,\mathtt{msg}_3))\\ &\quad \Rightarrow \mathtt{Send}(\mathtt{T}_1,\mathtt{msg}_2) \lhd \mathtt{Receive}(\mathtt{T}_2,\mathtt{msg}_3)\end{aligned}$$

$$
\mathit{true}[\texttt{Initiator}(\texttt{A},\texttt{B})]_{\texttt{T}}
\left(\begin{array}{l}
\texttt{Honest}(\texttt{B}) \wedge \texttt{B} \neq \texttt{A} \\
\Rightarrow \left(\begin{array}{lcl}
\exists \texttt{T}\prime : \texttt{T}\prime\texttt{.pname} = \texttt{B} & & \\
\wedge \texttt{Send}(\texttt{T}, \texttt{acq\_req\_A}) & \lhd & \texttt{Receive}(\texttt{T}\prime, \texttt{act\_req\_B}) \\
\wedge \texttt{Receive}(\texttt{T}\prime, \texttt{acq\_req\_B}) & \lhd & \texttt{Send}(\texttt{T}\prime, \texttt{act\_res\_B}) \\
\wedge \texttt{Send}(\texttt{T}\prime, \texttt{acq\_res\_B}) & \lhd & \texttt{Receive}(\texttt{T}, \texttt{act\_res\_A}) \\
\wedge \texttt{Receive}(\texttt{T}, \texttt{acq\_res\_A}) & \lhd & \texttt{Send}(\texttt{T}, \texttt{mac\_tag\_A}) \\
\wedge \texttt{Send}(\texttt{T}, \texttt{mac\_tag\_A}) & \lhd & \texttt{Receive}(\texttt{T}\prime, \texttt{mac\_tag\_A}) \\
\wedge \texttt{Receive}(\texttt{T}\prime, \texttt{mac\_tag\_A}) & \lhd & \texttt{Send}(\texttt{T}\prime, \texttt{mac\_tag\_B}) \\
\wedge \texttt{Send}(\texttt{T}\prime, \texttt{mac\_tag\_B}) & \lhd & \texttt{Receive}(\texttt{T}, \texttt{mac\_tag\_B})
\end{array}\right)
\end{array}\right)
$$

Figure 7.1: Authentication properties of the NFC-SEC-1 Initiator role. If Alice successfully completes the Initiator role, and if Bob was honest, then Alice knows that she communicated with Bob and that all messages were sent in the correct order.

7.4 Proof of Authentication

The PCL system is useful for proving two properties of protocols: authentication and secrecy. The axioms listed in Section 7.3 and those listed in [92] are sufficient to prove authentication of the NFC-SEC-1 protocol from both the Initiator and Target perspectives. Figure 7.1 shows the $\texttt{Auth}_{\texttt{INITIATOR}}$ property. It says that if Alice (A) performs the Initiator role, then if Bob (B) was honest, Alice knows that she communicated with Bob and that all of the messages transmited as part of the protocol were sent in the proper order.

Notice that during the key exchange part of the protocol, neither Alice nor Bob sends any identifying information. The nature of NFC itself demands that both Alice and Bob know each others NFCID3s, but those values are not used to derive `z_sse`. And, once Alice derives `z_sse`, she does not actually know if she has the same value as Bob until the key verification stage of the protocol. Thus, in order to prove the authentication property, we begin with the key verification stage.

Figure 7.2 shows a PCL proof of the authentication property for NFC-SEC-1 from the Initiator's perspective. In the first three steps, we define the message that Alice calls

$$
\begin{aligned}
\textbf{AA0}, \textbf{AA1} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_B} = \{|< \mathtt{02}, \mathtt{A}, \mathtt{B}, \mathtt{pk(A)}, \mathtt{pk(B)} >|\}^{\mathtt{S}}_{\mathtt{mk_{SSE}}} \\
\textbf{AA1} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_B} = \\
& \qquad \{|< \mathtt{02}, \mathtt{A}, \mathtt{B}, \mathtt{pk(A)}, \mathtt{pk(B)} >|\}^{\mathtt{S}}_{\{|<\mathtt{n\_A,n\_B,A,B,01}>|\}^{\mathtt{S}}_{\mathtt{keyseed}}} \\
\textbf{AA1} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_B} = \\
& \qquad \{|< \mathtt{02}, \mathtt{A}, \mathtt{B}, \mathtt{pk(A)}, \mathtt{pk(B)} >|\}^{\mathtt{S}}_{\{|<\mathtt{n\_A,n\_B,A,B,01}>|\}^{\mathtt{S}}_{\{|\mathtt{z\_sse}|\}^{\mathtt{S}}_{<\mathtt{n\_A,n\_B}>}}} \\
\textbf{HAS} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{Has(A,mac\_tag\_B)} \Rightarrow \mathtt{Receive(A,mac\_tag\_B)} \\
\textbf{AA0}, \textbf{AA1} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_vA} = \{|< \mathtt{02}, \mathtt{A}, \mathtt{B}, \mathtt{pk(A)}, \mathtt{pk_B} >|\}^{\mathtt{S}}_{\mathtt{mk_{SSE}}} \\
\textbf{AA1} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_vA} = \\
& \qquad \{|< \mathtt{02}, \mathtt{A}, \mathtt{B}, \mathtt{pk(A)}, \mathtt{pk_B} >|\}^{\mathtt{S}}_{\{|<\mathtt{n\_A,n\_B,A,B,01}>|\}^{\mathtt{S}}_{\mathtt{keyseed}}} \\
\textbf{AA1} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_vA} = \\
& \qquad \{|< \mathtt{02}, \mathtt{A}, \mathtt{B}, \mathtt{pk(A)}, \mathtt{pk_B} >|\}^{\mathtt{S}}_{\{|<\mathtt{n\_A,n\_B,A,B,01}>|\}^{\mathtt{S}}_{\{|\mathtt{z\_sse}|\}^{\mathtt{S}}_{<\mathtt{n\_A,n\_B}>}}} \\
\textbf{AA0} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{mac\_tag\_B} = \mathtt{mac\_tag\_vA} \\
\textbf{KEY}, \textbf{HON} \quad & \mathtt{Honest(A)} \wedge \mathtt{Honest(B)} \wedge \mathtt{Has(T\prime,z\_sse)} \Rightarrow \mathtt{T\prime.pname} = \mathtt{A} \vee \mathtt{T\prime.pname} = \mathtt{B} \\
\textbf{KEY}, \textbf{HON} \quad & \mathit{true}[\mathtt{Initiator(A,B)}]_{\mathtt{T}}\mathtt{Honest(B)} \Rightarrow \exists \mathtt{T\prime} : \mathtt{T\prime.pname} = \mathtt{B}
\end{aligned}
$$

Figure 7.2: A PCL proof of weak authentication for the NFC-SEC-1 Initiator role. The first column refernces the axioms as they are labeled in [92]. Here, Alice and Bob are called A and B, respectively.

`mac_tag_B`. In step four, we reason that either Alice generated `mac_tag_B` or she received it as a message. From examining the protocol in Algorithm 7.1, it is clear that Alice did not generate `mac_tag_B`. Therefore, she received it as a message. Steps five through seven define `mac_tag_vA`, which is constructed with `z_sse`. Step eight notes that if Alice completed the Initiator role, then `mac_tag_B` is equal to `mac_tag_vA`. Step nine says that if Bob is honest, then only he and Alice have `z_sse`. Thus, Bob must have generated the message that Alice received and weak authentication is proved, as shown in step ten. Note that if `mac_tag_B` and `mac_tag_vA` did not contain "A" and "B", then a dishonest party could have performed the key exchange with Alice and she would be none the wiser since the NFC-SEC-1 protocol does not verify that public keys belong to specific parties.

The proof in Figure 7.3 shows that all messages were received in the correct order. The first step says that if Alice generated a fresh nonce and sent a message containing it, and then Bob received a message containing that nonce, then Alice sent her message before Bob received his. Observation of the protocol shows that Bob receives `act_req_B` before sending `act_res_B`. Likewise, Bob must have sent his new nonce before Alice received it and, by observation, Alice must have received `act_res_A` before sending `mac_tag_A`.

The second step uses the new FS3 axiom to show that since `mac_tag_A` was `Fresh` before Alice sent it, then she must have sent it before Bob received it. Observation of the protocol and a second application of FS3 show that the final message, `mac_tag_B` was sent and received in the proper order, thus proving strong authentication.

Since the Initiator and Target perform essentially the same functions in the NFC-SEC-1 protocol, the $\texttt{Auth}_{\texttt{TARGET}}$ property would look very similar to $\texttt{Auth}_{\texttt{INITIATOR}}$ in Figure 7.1 and the proofs of authentication would be nearly identical to the ones in Figures 7.2 and 7.3.

7.5 Chapter Summary

Protocol Composition Logic (PCL) provides a framework for proving the security properties of network protocols. In this chapter, PCL is used to provide a proof of the authentication property of the NFC-SEC-1 protocol's Shared Secret Service (SSE) from the perspectives of both the Initiator and Target devices.

$$\begin{array}{rl}
\mathbf{FS2}, \mathbf{AA4} & \mathit{true}[\texttt{Initiator(A,B)}]_{\texttt{T}}\texttt{Honest(B)} \Rightarrow \exists \texttt{T}' : \texttt{T}'\texttt{.pname} = \texttt{B} \\
& \wedge \texttt{Send(T,} \texttt{acq\_req\_A)} \lhd \texttt{Receive(T}', \texttt{act\_req\_B)} \\
& \wedge \texttt{Receive(T}', \texttt{acq\_req\_B)} \lhd \texttt{Send(T}', \texttt{act\_res\_B)} \\
& \wedge \texttt{Send(T}', \texttt{acq\_res\_B)} \lhd \texttt{Receive(T,} \texttt{act\_res\_A)} \\
& \wedge \texttt{Receive(T,} \texttt{acq\_res\_A)} \lhd \texttt{Send(T,} \texttt{mac\_tag\_A)} \\
\mathbf{FS3} & \mathit{true}[\texttt{Initiator(A,B)}]_{\texttt{T}}\texttt{Honest(B)} \Rightarrow \exists \texttt{T}' : \texttt{T}'\texttt{.pname} = \texttt{B} \\
& \wedge \texttt{Send(T,} \texttt{acq\_req\_A)} \lhd \texttt{Receive(T}', \texttt{act\_req\_B)} \\
& \wedge \texttt{Receive(T}', \texttt{acq\_req\_B)} \lhd \texttt{Send(T}', \texttt{act\_res\_B)} \\
& \wedge \texttt{Send(T}', \texttt{acq\_res\_B)} \lhd \texttt{Receive(T,} \texttt{act\_res\_A)} \\
& \wedge \texttt{Receive(T,} \texttt{acq\_res\_A)} \lhd \texttt{Send(T,} \texttt{mac\_tag\_A)} \\
& \wedge \texttt{Send(T,} \texttt{mac\_tag\_A)} \lhd \texttt{Receive(T}', \texttt{mac\_tag\_A)} \\
\mathbf{AA4}, \mathbf{FS3} & \mathit{true}[\texttt{Initiator(A,B)}]_{\texttt{T}}\texttt{Honest(B)} \Rightarrow \exists \texttt{T}' : \texttt{T}'\texttt{.pname} = \texttt{B} \\
& \wedge \texttt{Send(T,} \texttt{acq\_req\_A)} \lhd \texttt{Receive(T}', \texttt{act\_req\_B)} \\
& \wedge \texttt{Receive(T}', \texttt{acq\_req\_B)} \lhd \texttt{Send(T}', \texttt{act\_res\_B)} \\
& \wedge \texttt{Send(T}', \texttt{acq\_res\_B)} \lhd \texttt{Receive(T,} \texttt{act\_res\_A)} \\
& \wedge \texttt{Receive(T,} \texttt{acq\_res\_A)} \lhd \texttt{Send(T,} \texttt{mac\_tag\_A)} \\
& \wedge \texttt{Send(T,} \texttt{mac\_tag\_A)} \lhd \texttt{Receive(T}', \texttt{mac\_tag\_A)} \\
& \wedge \texttt{Receive(T}', \texttt{mac\_tag\_A)} \lhd \texttt{Send(T}', \texttt{mac\_tag\_B)} \\
& \wedge \texttt{Send(T}', \texttt{mac\_tag\_B)} \lhd \texttt{Receive(T,} \texttt{mac\_tag\_B)}
\end{array}$$

Figure 7.3: A PCL proof of strong authentication for the NFC-SEC-1 Initiator role. This proof relies on the result from the proof in Figure 7.2.

Chapter 8

Conclusions

8.1 Summary and Accomplishments

As Near Field Communication (NFC) technology matures, it will increasingly become part of daily commerce. Therefore, NFC transactions must be as secure as possible. This dissertation examined the known weaknesses of NFC technology, such as eavesdropping attacks and relay attacks, as well as its inherent defenses, such as its short communication range.

A new test and development platform utilizing a combination of commercial, off-the-shelf components will allow future researchers and engineers to find weaknesses in NFC protocols and to develop defenses against them. This new test platform uses hardware that is very similar to that found in typical smart phones and which is compatible with nearly all other NFC and RFID devices currently on the market. All of the hardware and software comprising the new test and development platform is open source, enabling future users to modify it as necessary.

Using the new test platform, this dissertation presented a situation in which the single-device detection protocol failed to ensure a proper pairing of NFC devices. This failure leaves NFC transactions open to bad actors and is easily reproduced. One possible defense against this problem is the NFC-SEC protocol, which provides for secure key exchanges and encrypted datagrams.

The NFC-SEC protocol itself specifies only a framework for security services. The more specific NFC-SEC-1 protocol provides the details, including elliptic curve Diffie-Hellman key exchanges and AES data encryption. Using a framework called Protocol Composition Logic, this dissertation examined the NFC-SEC-1 protocol and proved that it is sound for authentication purposes. With NFC-SEC-1, two honest actors can ensure that they are communicating with one another and that all of their messages are sent and received in the correct order, regardless of any attackers.

8.2 Future Work

While the NFC-SEC protocol is sufficient to secure some NFC transactions, others cannot benefit from its services. Even then NFC-SEC is employed, security might not be sufficient. Therefore, further research with the test and developoment platform and other test equipment is necessary to improve the security of NFC technology. Some possible areas of exploration include:

- *Prove the secrecy properties of NFC-SEC-1 with PCL.* While this dissertation was able to show that NFC-SEC-1 provides proper authentication services, it did not attempt to show that the protocol provides secrecy of data. Proving the secrecy properties of NFC-SEC-1 is essential to understanding it.

- *Fix the double target problem.* Whether the result of a bug in the libnfc software or a flaw in the PN532 module, the double target problem is easily reproducable and could cause significant interference for legitimate transactions. Therefore, a fix for the single-device detection protocol to migitate this problem would be beneficial.

- *Update the test and development platform.* Adding additional NFC devices, including some that employ the NFC-SEC protocol, would allow developers to test vulnerabilities and defenses in more realistic situations. Many NFC readers use a standard USB interface, which the test platform provides. Additionally, the test platform currently runs a somewhat outdated version of Ubuntu Linux. Future iterations of the platform might use a newer release or switch to the Android operating system to better emulate current smart phones.

- *Improve the libnfc library.* The libnfc library is both free and open source and supports a large selection of NFC and RFID devices. While it does an adequate job of implementing low-level device drivers, it lacks higher-level interfaces for easily sending NFC messages in raw or NDEF format. Further, the library appears to be lacking full support for the PN533 device's NFC-SEC features. Improvements to libnfc would benefit all NFC developers and researchers.

8.3 Resulting Publications

- Steven J. Olivieri, Nicholas A. F. DeMarinis, Alexander M. Wyglinski. "On Protocol Architectures for Near Field Communication Systems: An Overview." *Wiley Journal on Wireless Communications and Networks*, April 2015 (Submitted).

- Steven J. Olivieri, Nicholas A. F. DeMarinis, Alexander M. Wyglinski. "A Tutorial on Near Field Communication Security Protocols." *Elsevier Computer Communications*, April 2015 (Submitted).

- Steven J. Olivieri, Nicholas A. F. DeMarinis, Alexander M. Wyglinski. "Analyzing NFC-SEC with Protocol Composition Logic." *Wiley Security and Communication Networks*, April 2015 (Submitted).

Appendix A

Multiplying in Finite Fields

The peasant algorithm is an ancient form of multiplication that was used in at least Egypt, Russia, and Ehtiopia. It allows one to multiply two numbers using only doubling, halving, and summing. Thus, it was easier to learn than multiplication tables and methods that we use today.

A.1 Peasant Algorithm

To begin, determine the two multiplicands. As an example, let us use 327 and 15. Next, decompose the larger of the two multiplicands. To do so, first find the largest power of two in the larger of the two multiplicands. Begin with the number 1 and multiply by 2 until the result is larger than the multiplicand.

$$\begin{array}{rcr} 1 \times 2 & = & 2 \\ 2 \times 2 & = & 4 \\ 4 \times 2 & = & 8 \\ 8 \times 2 & = & 16 \\ 16 \times 2 & = & 32 \\ 32 \times 2 & = & 64 \\ 64 \times 2 & = & 128 \\ 128 \times 2 & = & 256 \\ 256 \times 2 & = & 512 \end{array}$$

So, the largest power of 2 in 327 is 256. Continue the decomposition by subtracting 256 and then finding the next power of two that is smaller than the result of the subtraction. Repeat this process until nothing remains.

$$\begin{array}{rcrcr} 327 & - & 256 & = & 71 \\ 71 & - & 64 & = & 7 \\ 7 & - & 4 & = & 3 \\ 3 & - & 2 & = & 1 \\ 1 & - & 1 & = & 0 \end{array}$$

Thus, the multiplicand 327 is the sum of 256, 64, 4, 2, and 1. Next, create a table consisting of doubles of the second multiplicand, 15. Stop when the power of two is the largest component of the first multiplicand.

$$\begin{array}{rcrcr} 15 & \times & 1 & = & 15 \\ 15 & \times & 2 & = & 30 \\ 15 & \times & 4 & = & 60 \\ 15 & \times & 8 & = & 120 \\ 15 & \times & 16 & = & 240 \\ 15 & \times & 32 & = & 480 \\ 15 & \times & 64 & = & 960 \\ 15 & \times & 128 & = & 1920 \\ 15 & \times & 256 & = & 3840 \end{array}$$

Finally, sum the doubles of the second multiplicand that correspond to the components of the first multiplicand.

$$\begin{array}{rcrcr}
15 & \times & 1 & = & \mathbf{15} \\
15 & \times & 2 & = & \mathbf{30} \\
15 & \times & 4 & = & \mathbf{60} \\
15 & \times & 8 & = & 120 \\
15 & \times & 16 & = & 240 \\
15 & \times & 32 & = & 480 \\
15 & \times & 64 & = & \mathbf{960} \\
15 & \times & 128 & = & 1920 \\
15 & \times & 256 & = & \mathbf{3840}
\end{array}$$

So, the product of 327 and 15 is $15 + 30 + 60 + 960 + 3840 = 4905$.

A.2 Finite Fields

Recall from Section 3.1.1 that numbers used in the AES algorithm are elements of a finite field. Specifically, the Galois field GF(2^8) with irreducible polynomial $m(x) = x^8+x^4+x^3+x+1$. We can represent values in this field with binary notation. For example, the value 21 in GF(2^8) is "$x^4 + x^2 + 1$", which we represent as "00010101". Multiplying numbers in GF(2^8) is complex, but a modified version of the peasant algorithm makes the operation simpler.

As before, first determine the two multiplicands. The multiplicands must be elemnts of the finite field, so their range is restricted to $[0, 255]$. For this example, we use `A` $= 145$ and `B` $= 21$. In binary notation, the multiplicands are `A` $=$ 10010001 and `B` $=$ 00010101. Initialize the product, `P`, to zero. Next, we run a series of binary arithmetic operations eight times, once for each bit in either of the multiplicands.

First, check if the rightmost bit of `B` is set. If so, then exclusive-OR `P` with the value of `A`. As described in Section 3.1.1, this operation is equivalent to addition in the finite field. Next, shift `B` one bit to the right, setting the leftmost bit to zero and discarding the x^0 term. Now, check the leftmost bit of `A`, which represents the x^7 term of the polynomial. If it is set to one, then set a variable called `carry` to true. Shift `A` left one bit, multiplying it by x. Finally, if `carry` was set to true, then exclusive-OR `A` with the binary value "00011011", which represents the irreducible polynomial with the x^8 term removed. This final step is necessary because $\mathtt{A} \times x$ must be calculated modulo 2 in GF(2^8).

After all eight iterations, the value of `P` is the desired product. Algorithm A.1 shows a sample implementation of the modified peasant algorithm in C. As a minor optimization, the loop terminates when either `A` or `B` is zero.

Running this implementation with the example multiplicands 145 and 21 produces the following output. Here, the values are printed in hexadecimal notation for simplicity.

```
a=91    b=15

0: a=39    b=0A    p=91
1: a=72    b=05    p=91
2: a=E4    b=02    p=E3
3: a=D3    b=01    p=E3
4: a=BD    b=00    p=30

p=30
```

The loop terminates after five iterations since the decomposition is complete. Note that as with the original peasant algorithm, `A` should be the larger multiplicand and `B` the smaller. On average, setting the multiplicands this way will result in fewer iterations of the loop. If we set them the opposite way in this example, then the loop requires all eight iterations to compute the product.

```
a=15    b=91

0: a=2A    b=48    p=15
1: a=54    b=24    p=15
2: a=A8    b=12    p=15
```

```
3: a=4B     b=09     p=15

4: a=96     b=04     p=5E

5: a=37     b=02     p=5E

6: a=6E     b=01     p=5E

7: a=DC     b=00     p=30


p=30
```

Algorithm A.1: The modified peasant algorithm in C.

```
#include <stdbool.h>
#include <stdint.h>
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char* argv[]) {
        uint8_t a = 0, b = 0, p = 0;
        bool carry = false;

        if (argc != 3) {
                fprintf(stderr, "usage: peasant a b\n");
                return EXIT_FAILURE;
        }

        a = atoi(argv[1]); b = atoi(argv[2]);
        fprintf(stdout, "a=%02X      b=%02X\n\n", a, b);

        for (uint8_t i = 0; i < 8, a != 0, b != 0; ++i) {
                if (b & 0x01) {
                        p ^= a;
                }
                carry = (a & 0x80);
                a <<= 1;
                if (carry) {
                        a ^= 0x1B;
                }
                b >>= 1;
                fprintf(stdout, "%d: a=%02X      b=%02X      p=%02X\n", i,
                    a, b, p);
        }

        fprintf(stdout, "\np=%02X\n", p);
        return EXIT_SUCCESS;
}
```

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