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Moving target network steganography

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MOVING TARGET NETWORK STEGANOGRAPHY

by

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Dedications

To my family and friends. Without you, this would not have been possible.

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Abstract

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A branch of information hiding that has gained traction in recent years is network steganography. Network steganography uses network protocols are carriers to hide and transmit data. Storage channel network steganography manipulates values in protocol header and data fields and stores covert data inside them. The timing channel modulates the timing of events in the protocol to transfer covert information. Many current storage channel network steganography methods have low bandwidths and they hide covert data directly into the protocol which allows discoverers of the channel to read the confidential information. A new type of storage channel network steganography method is proposed and implemented which abstracts the idea of hiding data inside the network protocol. The addition of a moving target mechanism rotates the locations of data to be evaluated preventing brute force attacks. The bandwidth of the algorithm can also be controlled by increasing or decreasing the rate of packet transmission. A proof of concept is developed to implement the algorithm. Experimental run times are compared with their theoretical equivalents to compare the accuracy of the proof of concept. Detailed probability and data transfer analysis is performed on the algorithm to see how the algorithm functions in terms of security and bandwidth. Finally, a detection and mitigation analysis is performed to highlight the flaws with the algorithm and how they can be improved.

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Chapter 1

Covert Channels and Network Steganography

Covert Channels

The term “covert channel” originally coined by Butler Lampson [1], is defined by the United States Department of Defense as “any communication channel that can be exploited by a process to transfer information in a manner that violates the system’s security policy” [2]. In plain terms, a covert channel is an information hiding technique in which the user takes advantage of the design and availability of a standard communication channel to transfer covert data between two processes or entities without a third party knowing of its existence. It is important to note that the term “covert channel” is used to describe a category of information hiding techniques and not a singular entity by itself. Figure 1 describes the information hiding hierarchy.

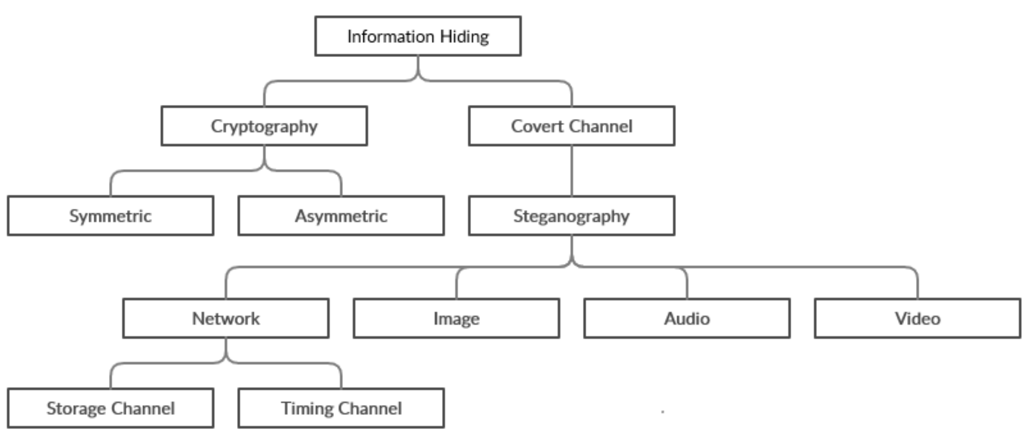


Figure 1. Information hiding hierarchy

One of the most widely known and used covert channels is steganography. Steganography is the practice of hiding a message inside a carrier and comes from the Greek word “steganos” which means “covered” or “protected” and “kryptos”, meaning hidden (secret) [3] [4]. A point to note is that steganography is not the same as cryptography. Although both prominent techniques of information hiding, steganography aims to hide the existence of a message while cryptography aims to hide the content of a message [5].

The most popular form of steganography is image steganography where data is hidden inside images. Software such as BPStegno [6], StegHide [7], and OpenStego [8] use different encoding techniques to hide data inside of the image pixels, the most common being Least-Significant Bit (LSB) but there are many more techniques. The LSB data encoding technique encodes data inside the least-significant bit of the image pixel’s red, green, and blue values. By using LSB encoding, the sender can hide up to 3 bits of data inside every pixel without significantly impact the visual quality of the images.

While image steganography is the most widely used and recognizable forms of steganography, a new type of steganography, using network protocols as carriers, has gained traction in recent years. The term “network steganography” was first introduced by Krzysztof Szczypiorski in 2003 [9]. Network steganography is a subset of steganography where network protocols are used as carriers to hide and transmit secret messages. For a simple example of network steganography imagine a communication protocol which is used by two parties to exchange messages. The communication protocol assumes that the response from either side should come within a specific amount of time after the initial message was sent, otherwise the response will be treated as a delayed message and discarded. The two parties want to communicate in secret, agree that responses carrying the secret messages will be purposely delayed and not be discarded by the recipient but instead read to extract the secret message. This becomes their shared secret. The manipulation of the communication protocol happens in the intentional delaying of responses containing the secret messages. Third parties who observe the network traffic between our two parties do not become suspicious of the existence of a hidden communication channel if the frequency of delayed responses does not appear to be out of the ordinary, e.g., under a certain threshold. This example of network steganography is categorized as a timing channel approach which is discussed later in this chapter [4].

The Prisoner's Problem

A classic problem used to define the need for a covert channel is the Prisoners Problem [10]–[12]. The prisoners problem was introduced by Gustavus J. Simmons in 1983 [10] and is used to describe a scenario in which covert channels are needed to communicate. Figure 2 (adapted from [11]) shows the prisoners problem. There are two prisoners, Alice and Bob, and they want to communicate with each other to plan their escape. Both Alice and Bob are confined to their prison cell and can only communicate using the provided computer terminals. The network used for communication is insecure and monitored by the Warden, Walter. He is monitoring the network for evidence of any malicious activity by Alice or Bob. The use of cryptography would immediately be noticed by the Warden causing him to throw Alice and Bob into solitary confinement where they would not be able to communicate with each other. Therefore, cryptography cannot be used to secure their exchange of secret messages. Alice and Bob must communicate in such a way over the unsecure network that the warden does not find out their plan to escape the prison. A point to note is that Alice and Bob have a shared secret between them. Without the shared secret, the receiver might as well be the warden because there is no way to differentiate normal traffic from the covert traffic. How the shared secret is established is beyond the scope of this research, but they could have met in private to share the secret. There are two types of wardens in the prisoners problem, an active warden and a passive warden. The active warden can modify the contents of the network traffic in any way he wants and can be more aggressive. The passive warden is like a network sniffer and can only spy on the network traffic, he cannot alter the messages in any way.

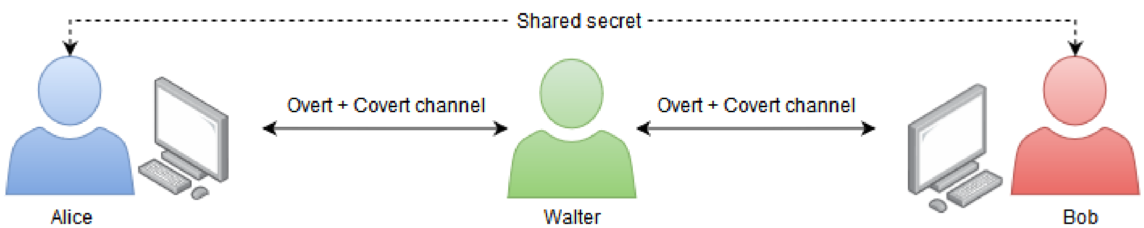


Figure 2. The Prisoner's Problem

The goal of network steganography is to send covert data through regular network channels which cannot be detected by the warden or any other third party for that matter. Many classical schemes can be easily detected by the warden because they manipulate the protocol in an un-natural or predictable way which does not conform to the standards set in place.

Overview of TCP/IP

Network steganography exists partly because of the adaption of an open system architecture of the Internet and the standardization of communication protocols. The Internet, the largest network on the planet, is made up of millions of servers, routers, switches, and end-users. These devices communicate with each other using standardized communication protocols to form the Internet. These protocols, designed in the 1970s, 1980s, and 1990s, form the backbone of the communication architecture of the Internet as we know it today. One of those protocol suites, the TCP/IP Protocol Suite (Transmission Control Protocol and Internet Protocol) [13], is widely used on the Internet today. Created by the United States Department of Defense in collaboration with several academic institutions [14], the TCP/IP protocol was created to meet the demands of an increasingly connected world. Since the creation and adoption of the TCP/IP protocol, the Internet has grown exponentially in size and far beyond its original scope [14]. The Internet has evolved from a simple network between a small number of federal and academic organizations to a global network connecting millions of people, thanks in part to the TCP/IP protocol suite.

The popularity of TCP/IP is due in part to its robustness and its open, free, and broad protocol standard. TCP/IP can operate on different types of physical transmission mediums such as Ethernet, optical, and dial-up which allows it to integrate into many different kinds of networks [14]. Because it was so widely supported by different organizations, TCP/IP is designed to work independently from specific types of hardware or operating systems, allowing it to be used in many different communication scenarios [14].

The TCP/IP communication suite works using a layered approach. Figure 3 shows the layers of the TCP/IP protocol stack. There are 5 layers in the TCP/IP protocol stack with the Physical Layer denoted as the first layer and the Application Layer referenced as the fifth layer.

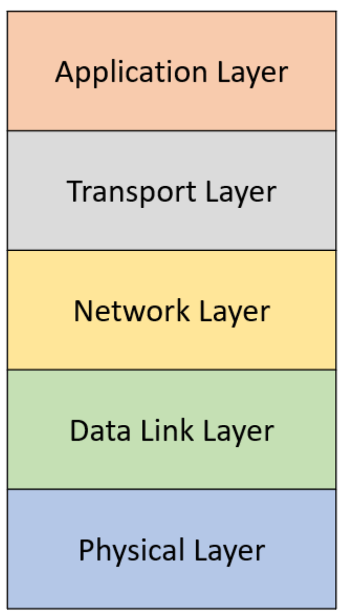


Figure 3. Layers of the TCP/IP Protocol Suite

The application layer oversees the receiving and sending of data to and from the user. The protocols in this layer are used to provide services such as file sharing (FTP

[15], SFTP [16]), remote login capability (TELNET [17], SSH [18]), mail transfer (SMTP [19], IMAP [20], POP3 [21]), and web page delivery (HTTP [22], HTTPS [23]) to name a few [14]. New protocols are constantly added to this layer to extend the functionality of this layer.

The transport layer is one of the most important layers of the TCP/IP stack and the fourth layer. It controls the delivery of data between two processes on different hosts. Two of the most popular transport layer protocols are the Transmission Control Protocol (TCP) [24] and User Datagram Protocol (UDP) [25].

TCP is a reliable connection-oriented protocol, which means that it will try to send data in a reliable manner and has mechanisms to prevent data (called packets) from being lost or dropped between the source and destination [14]. TCP has an acknowledgement mechanism which allows the sender to send data again if an acknowledgement that the data has arrived has not been sent by the receiver does not arrive. TCP also provides checksums or data hashes which are used to verify the integrity of the data. If the data is received undamaged and unaltered, the receiver sends a positive acknowledgement to the sender. If the data is damaged or altered, the receiver sends a negative acknowledgement to the sender and the sender can resend the data [14].

Being a connection-oriented protocol, TCP establishes a logical end-to-end connection between two hosts [14] before sending data. The establishment of this logical connection is called a “three-way handshake”. Figure 4 shows a simple implementation of the three-way handshake.

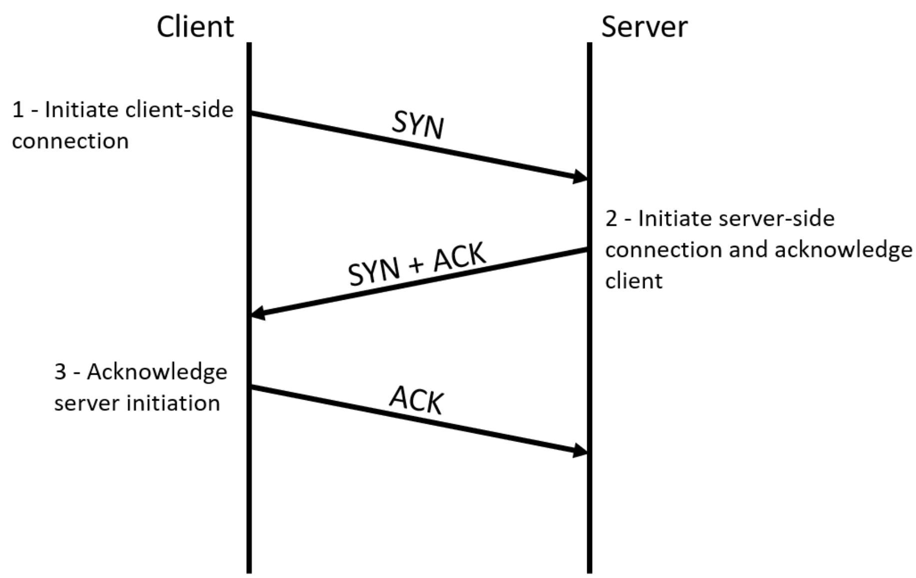


Figure 4. TCP three-way handshake

The first step in the three-way handshake is the SYN step. The client initiates a connection by sending a “SYN” packet to the server. SYN is a flag in the TCP protocol which means synchronize and is used to initiate connections. This means that the client wants to start a connection with the server. The second step is the SYN+ACK step performed by the server. The server sends the client a SYN+ACK packet. The packet sent by the server has two flags set, the SYN flag and the ACK flag. The ACK flag stands for acknowledge. The server acknowledges to the client that it received the connection initiation request sent by the client (the SYN packet) and it also wants to open a connection from the server’s side, which is marked by the SYN flag sent alongside the ACK flag. The third step is the ACK step sent by the client to the server. The client receives the SYN+ACK packet from the server in step two and proceeds to acknowledge that the server wants to initiate a connection as well. The client also acknowledges that the server acknowledged the client wanting to open a connection. After the third step is complete, both the client and server have established a connection which is acknowledged by the other party creating a reliable and connection-oriented path to exchange data. The termination of the logical connection happens in the same format. The flag used to terminate the connection is FIN which signals the end of data transmission from the sender.

UDP is the second most popular transport layer protocol in the TCP/IP stack. It is an unreliable connectionless protocol, where "unreliable" means that UDP does not have any way to verify that the data has reached the receiver [14]. UDP delivers data correctly by using the IP address of the destination machine and the port number of the process. Since UDP does not have a data received verification mechanism, it is a more efficient choice as a transport layer protocol because there is no overhead of creating and maintaining a reliable connection [14]. Media applications and services may prefer using UDP over TCP because of its speed in transferring information.

The network layer is the third layer in the TCP/IP protocol suite. The most popular and widely used network protocol is the Internet Protocol (IP) version 4 (IPv4) [26]. The IP protocol creates data fragments called datagrams which are the basic unit of transmission for the Internet, defines a common addressing scheme for devices connected to the Internet, controls the routing of datagrams between hosts, and performs fragmentation and de-fragmentation of datagrams [14]. The IP protocol uses IP addresses as a common addressing scheme for devices connected to a network. An IP address is like a house address. Every house has a different address and in the same way, each host has a different IP address. The IP address is used to deliver the data of the previous layers to the correct destination machine. The IP protocol also handles the fragmentation and de-fragmentation of datagrams if needed. Fragmentation breaks datagrams into smaller pieces and may be needed if the datagram is too large to be sent as a single unit [14].

Another important protocol in the network layer is the Internet Control Message Protocol (ICMP) [27]. ICMP is used to send messages which perform flow control and error reporting by sending messages between hosts through the network layer [14]. The ICMP protocol can notify the sender to stop sending datagrams temporarily to control the flow of traffic and about unreachable hosts among other notifications.

The second layer is the data link layer. Data at this layer is encapsulated inside frames. The function of the data link layer is to transfer frames between hops in the network. A hop or network node is every intermediate stop the frame makes between the source and destination, e.g., a router or a switch. The data link layer, like the transport and network layer, adds a header to the data frame with the source and destination physical addresses. The data link layer can also add a trailer. A trailer is another header that is added to the end of the frame instead of the front. The trailer contains data for error detection [28]. Some of the protocols supported by the data link layer include the IEEE 802.3 Ethernet standard [29] and the IEEE 802.11 Wireless LAN (WLAN) standard [30]. The IEEE 802.3 Ethernet standard defines the physical layer of a wired connection within a network. The IEEE 802.11 WLAN standard defines the physical layer of a wireless physical layer also known as Wi-Fi.

The first layer is the physical layer. The physical layer takes care of sending and receiving the data between hops. The data is sent a bit at a time and the protocol defined by the connection link is used, e.g., if two hops are connected by an ethernet link, the ethernet protocol is used to send the data. The physical layer is also tasked with controlling the direction of transmission between two devices: simplex, half-duplex, or full-duplex [31]. Simplex mode means only one device can send, and one can receive, in half-duplex mode, two devices can send and receive but not at the same time, and in full-duplex mode, two devices can send and receive at the same time [31].

Each layer is abstracted from the others to divide the functionality and prevent a single layer from performing too many tasks which can create a single point of failure. This allows the protocol to be modular and robust because each layer is its own system that receives and passes data to and from other layers and does not have to worry about the functionality of other layers. Each layer adds a header to the front of the data that it receives from the previous layer. The addition of each layer header is called encapsulation. Figure 5 [31] shows the encapsulation process.

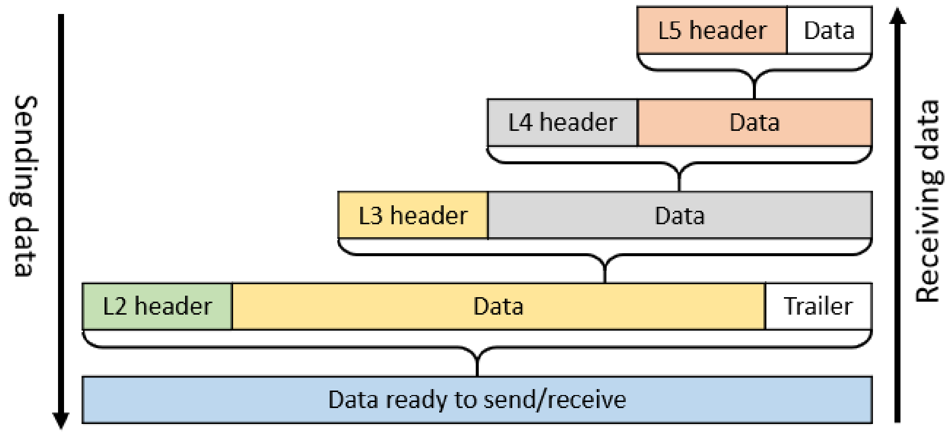


Figure 5. TCP/IP encapsulation process

There are many moving parts in the TCP/IP protocol suite. Each layer has a specific job which requires many unique protocols to accomplish. The variety of protocols and the availability of the TCP/IP protocol suite in today's Internet make it an increasingly attractive carrier for steganographic activity. Network steganography relies on three characteristics of current implementations of network protocols to transfer covert information [32]. The communication channels are not perfect. Data loss, corruption, and reordering happen in a real-world environment and thus it is possible to embed data by mimicking those behaviors [32]. Most network protocols define header fields or messages that are not used in all situations allowing users to hide data inside these extra fields [32]. Finally, not every protocol is completely defined and "semantic overloading" is possible [32], allowing a certain degree of freedom in the implementation. This freedom can be used for steganographic purposes to hide data.

Network Steganography

There are two types of network steganography, storage channel and timing channel. A storage channel is a class of network steganography that modifies values in the carrier to create a storage covert channel [32]. Typically, these techniques hide information by modifying protocol header fields, such as unused bits of a header, or the data field of a packet [32]. A majority of network steganography comprises of storage channel network steganography since each layer adds some type of header to the data it receives and not every field in the header is used.

A timing channel is a class of network steganography that modifies the timing of “events” in a carrier to create a timing covert channel [32]. The goal of a timing covert channel is to store information in the timing of the protocol messages or packets [32]. Timing channels are less prevalent in network steganography due to the increased complexity and limited user control over how the protocol and operating system handles the timing of the events. Much of the protocol timing is out of the users’ control, therefore, making timing channel steganography harder to implement and develop.

Two major drawbacks of current storage channel network steganography techniques are that they transmit actual covert data inside the channels and their transmission rate is low. Current network steganography channels embed the actual covert data inside the protocol allowing a third party to read the data if the covert channel is ever found. Additionally, since the confidentiality of the channel must be preserved, the transmission rate of the channel suffers because there are not many modifications that can be made to the protocol.

A new type of storage channel network steganography, moving target network steganography, is proposed and implemented to address these drawbacks. The new technique abstracts the transmission of data to each host by evaluating a data packet using hashing algorithms. Hashing data packets at the host level and comparing bits of the hash to covert data at the client level prevents covert data from being embedded inside a packet. Furthermore, by moving the locations and order of data that is evaluated to places known only by the hosts, it is virtually impossible to extract data from a packet if the scheme is detected. The scheme also has a higher average transmission rate than the 1 bit per second defined by the United States Department of Defense [2].

The rest of the thesis is organized as follows, Chapter 2 reviews current approaches in storage channel network steganography and touches on timing channel network steganography. Chapter 3 provides an in-depth explanation of the steganographic algorithm, the proof of concept, and reviews the results of the implementation. Chapter 4 contains a probability and data transfer analysis alongside mitigation techniques. Chapter 5 concludes the research.

Chapter 2

Related Network Steganography Approaches

In this chapter, related storage channel network steganography approaches are discussed and explained.

Kadhim et al. [33] proposed a network steganography technique based on crafting custom TCP/IP sequence numbers. Their algorithm performs the XOR operation on the binary representation of the secret data with the binary representation of the source port and destination port numbers. This number, converted to a decimal, is used as the sequence number. The receiver reads the data by performing the XOR operation with the received packet's sequence number, source port and destination port.

Kundur et al. [34] proposed a network steganography method based on manipulating the Do not Fragment (DF) IP header field which marks the packet as "don't fragment" [4]. The DF field which can hold either a "0" or a "1" and can be exploited by knowing the Maximum Transmission Unit (MTU) size which is the maximum size of a datagram that can be sent through a network [4]. Any datagram whose size is below the MTU value is not fragmented, thus rendering the DF field useless if set to "1". Therefore, by crafting datagrams whose size is less than the MTU value, the DF field value can be used to transmit one bit of covert data per packet.

Biswas et al. [35] proposed a network steganography technique which fills the TCP data portion with encrypted RSA data. The decryption key is then encoded inside the sequence number of the data packet and sent along with the encrypted data. The receiver sniffs TCP traffic from the sender, extracts the encrypted data from the TCP data field, and decrypts it using the key inside the sequence number field.

Stødle [36] proposed a network steganography technique using ICMP echo request and reply packets. In this scheme, the client communicates with a remote proxy using ICMP echo requests. The remote proxy communicates with the client using ICMP reply packets. The remote proxy then establishes a TCP connection with a remote server e.g. a website server. In a communication scenario, the proxy converts incoming TCP data from the remote server into ICMP reply packets and sends them to the client. The client does the same except their packets are in the form of ICMP request packets when communicating with the proxy.

Handel et al. [37] proposed several network steganography techniques for the OSI model [38]. The first method proposed hides covert data inside unused portions of the data link layer frame. The covert data is stored inside the buffer, beginning at the end of the buffer and working towards the valid data. When the frame is transmitted, the entire buffer is sent which includes the valid data and the covert data. The second method described is hiding data inside the network layer. Inside the IP header, there is an 8-bit Type of Service (ToS) field. The two least-significant bits are unused and can store two bits of covert data per packet. The last method uses the 6-bit Reserved header field between the Header Length and the TCP Flags to store six bits of information. Combined with the IP ToS field's two bits and the six bits of the Reserved field, the sender can send one byte of covert information per packet.

Jankowski et al. [39] proposed a network steganography technique called PadSteg which uses inter-protocol network steganography and the EtherLeak [40] frame padding vulnerability to send covert data. Inter-protocol steganography exploits the relationship between two or more protocols from the TCP/IP stack to transmit covert information. The EtherLeak vulnerability is a flaw in the padding mechanism of many Network Interface Cards (NIC) where the physical layer (hardware implementation) or the data link layer (software implementation) do not properly zero out the padded bits of an ethernet frame. This allows arbitrary bits to be placed into the padding buffer thus allowing the storage of covert bits. PadSteg uses the ARP [41] protocol to search for hidden nodes on a LAN that can communicate secretly. Once a hidden node is found, both nodes take TCP data transmitted between each other and hide secret data inside the ethernet frame padding bits.

Melo et al. [42] described a network steganography technique using TCP sequence numbers. The method can transmit 3 bits of data inside the Initial Sequence Number (ISN) of a TCP connection. The covert data is converted into its binary representation and concatenated into a 24-bit binary string. The first byte of the 32-bit TCP ISN is an identifier. Together, they make up a 32-bit binary string. The sum of the high values (locations where the bit is 1) is taken and that generates the 10-digit ISN which contains the data.

Giffin et al. [43] developed a network steganography method based on rewriting the least significant bits of a TCP packet's timestamp field. By purposely delaying the processing of TCP packets by the kernel, the least significant bit of the TCP timestamp can be modified to hold a covert bit. Since TCP timestamps are based on internal timings of the host machine, on a slower connection, the least significant bits are effectively random.

Rowland [44] proposed three network steganography techniques that manipulated TCP/IP header fields to encode ASCII values for transmission. The first method replaces the IP identification field with the ASCII representation of the character to be encoded. The second method encodes ASCII values inside the TCP sequence number of the packet by converting the ASCII representation of the character into a 32-bit sequence number. The third method uses a "bounce" server to send data to a remote server anonymously. The data is hidden inside the TCP sequence number and the source IP address of the packet is the remote server's IP address. When the bounce server replies to an initial SYN packet, the response is sent to the remote server. The remote server takes the incoming packet and decodes the information by transforming the sequence number minus one back into the ASCII equivalent.

Trabelsi et al. [45] described a network steganography technique which uses the IP Record Route option [26] to hide data inside the IP header. The IP Record Route option is an option which, when set in the IP header, allows routers that handle the packet to log their own IP address into allocated space inside the packet's IP header. The IP Record Route option has three fields, the code field, the length field, and the pointer field. The code field tells the host what type of option it is. The length field specifies the total length of the option as it appears inside the IP datagram. The pointer field specifies the offset to the next available slot inside the option data. This is used to determine where the next location is for writing the hosts' IP address. Every time a host logs their IP address inside the record route option, the pointer field is incremented by 4 (4 bytes). When the pointer field’s value is greater than the length field, no more hosts can log their IP address inside the IP datagram and the hosts send the packet to its destination. The authors exploit this functionality by setting the initial pointer value to be larger than the length value. This prevents any logging of IP addresses and allows up to 36 bytes of secret data to be hidden inside the option. They also proposed the Covert File Transfer Protocol (CFTP) which is a client/server application that exploits the IP record route hiding method to tunnel the ICMP protocol inside the IP options allowing for a two-way communication channel between the client and the server.

Szczypiorski [9] presented HICCUPS (HIdden Communication system for CorrUPted networkS), a new type of network steganography which utilized the IEEE 802.11 WLAN protocol. HICCUPS created data frames with bad checksums as a method of creating additional on-demand steganographic bandwidth. The data frames with bad checksums would be discarded by hosts who did not know about the steganographic scheme. Hosts that knew about the scheme would not discard the data frames and extract the covert data from those frames.

Rios et al. [46] presented network steganography techniques in the Dynamic Host Control Protocol (DHCP) [47]. The first technique uses the XID field in the DHCP header. The XID field is the transaction ID which is a random number generated by the client and used by both the client and server to associate the messages and responses between a client and a server [47]. The XID field is 4 bytes long. Since the field uses randomly generated fields by the client, the client can store covert data inside the field and send it to the server. The server stores the data locally until the client signals the end of the covert data transmission. Once the end of transmission is received, the server can read the covert data from the XID field. The second technique uses the sname and file fields inside the DHCP header which are together 190 bytes in length. Both the sname and file fields consist of null-terminated ('\0') strings. Anything after the null termination is marked as garbage data. The strategy sends "empty" fields by setting the first byte to a null character allowing for a maximum of 190 bytes of covert data to be sent per packet including the null characters.

Patuck et al. [48] introduced several covert channels inside the Extensible Messaging and Presence Protocol (XMPP) [49]. XMPP relies on XML streams as a base for transferring data. The first covert channel exploits the type channel by alternating between the "normal" and "chat" values. The attribute is not used by the server and is passed as-is to the receiver. The second covert channel uses the ID element which is a unique alphanumeric string for use in tagging messages (like TCP sequence numbers). The covert data is encoded inside the least-significant bit of the ID element and sent to the receiver, similar to [43]. The third covert channel manipulates the xml:lang attribute. The xml:lang attribute is used to determine the language used in writing the message. By using language codes that represent roughly the same language (en-GB, en-US, etc.), covert data can be transmitted. The final covert channel modifies the contents of the body element. The body element is where the actual content of the message is stored. The methods of modifying the body element include leading and trailing spaces around the body text encoding up to 2 bits of information, replacing words with synonyms (likely to suffer from many false positives and low accuracy), and intentional spelling mistakes.

Chapter 3

Algorithm, Implementation, and Results

Background

Hash functions. Hash functions are mathematical functions that generate a unique fixed-sized string from an input of arbitrary size [50]. Figure 6 [51] describes the hashing process. The user has an arbitrarily sized message (*M*) which they send to the hashing algorithm (*H*). The hashing algorithm mathematically reduces the message into a unique and fixed-size output (*D*) called the message digest or a hash.

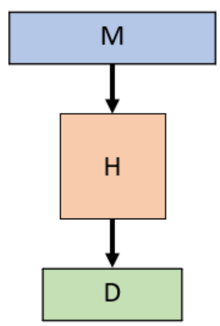


Figure 6. Hash function input and output

Hash functions are used for a wide variety of situations. Some of their many uses include digital signatures, integrity verification, message authentication, and password protection [51]. The properties that enable hash functions to be versatile are unpredictability, pre-image resistance, second pre-image resistance, and collision resistance [51]. Unpredictability is the property of a hash function that makes a hash function return a random unique string each time it receives an input [51]. Table 1 [51] shows an example of the unpredictability property. Three different inputs (numerals 1, 2, and 3) are hashed by the SHA-256 [52] hashing function and their output is shown. Even though 1, 2, and 3 are off only by one or two bits (0001, 0010, 0011), the output of the hash function is completely different for every input [51]. A point to note is that hash functions are always deterministic meaning they will always produce the same output for the same input.

Table 1

Hash function input and output examples

Hash function with input	Hash function output
SHA-256(1)	6b86b273ff34fce19d6b804eff5a3f5747ada4eaa22f1d49c01e52ddb7875b4b
SHA-256(2)	d4735e3a265e16eee03f59718b9b5d03019c07d8b6c51f90da3a666eec13ab35
SHA-256(3)	4e07408562bedb8b60ce05c1decfe3ad16b72230967de01f640b7e4729b49fce

Pre-image resistance describes the guarantee that given a random hash value, an attacker will never find a preimage of that hash value. A preimage of a given hash value, *D*, is any message, *M*, such that $H(M) = D$. Hash functions are also called one-way functions because a user can generate a hash from a message, but not a message from a hash, i.e. one-way. Pre-image resistance describes cases where it is practically (but not completely) impossible to find a message that hashes to a given hash value. Second pre-image resistance on the other hand, describes the cases that when given a message, *M* and its hash value *D*, it is practically impossible (but not completely) to find another message, *N*, that hashes to the same hash that *M* does. Pre-image resistance focuses on the hash functions ability to be irreversible, whereas second pre-image resistance focuses on the hash functions output being sufficiently random [51].

Collision resistance is the property that prevents two different input messages, *M* and *N*, from having the same hash, *D* [53] [51]. Collision resistance is related to second pre-image resistance in that if an attacker can find a second pre-image using a given message and its hash value, the attacker can also find collisions [51]. The reality of collisions is that they will always occur no matter what hashing algorithm is being used. This is due to the pigeonhole principle. The idea of the pigeonhole principle is that you have *K* holes and *R* pigeons to put into those holes, and if *R* is greater and *K*, at least one hole must contain more than one pigeon [51]. Hash functions produce a hash whose size is always the same, but they can take in a message that can of any length. This will always result in some messages having the same hash as other messages because the input can be, theoretically, any length. The goal is to make such a discovery practically impossible to detect and that is collision resistance.

Hash functions are an integral part of the proposed method because they provide a unique representation of data which allows the method to evaluate data packets and hide secret data inside of them without having to manipulate the packets directly.

Permutations. In mathematics, arranging objects in a certain order is called a permutation [54]. In contrast, a combination is a way of arranging objects where order doesn't matter. The numbers in the permutation do not have to increase linearly or consecutively. Each number can be greater or smaller than the previous number in the permutation. The sequence of numbers can also be described as a permutation array.

Another example of a permutation is choosing an ordered subset from a set of objects. How many ways can first place, second place, and third place be assigned to three people from a group of twenty people. In this example, order matters because there can only be one first-place winner, one second-place winner who cannot be either the first-place or the third-place winner, and one third-place who cannot be either the first-place or the second-place winner. Selecting an ordered subset out of a set is a selective permutation [55]. By leveraging selective permutations in the proposed method, a moving target feature is added. Selecting a random permutation array that is of a certain size out of a larger list of values allows the method to change the locations of where the secret data is hidden. Additionally, by seeding a random permutation array generator with a secret pre-shared key, the method prevents third parties from re-creating the same permutation arrays.

Algorithm

While traditional storage channel network steganography methods hide data directly into the fields of a packet, the proposed algorithm analyzes a packet in a holistic manner to hide and extract secret data. This allows the algorithm to stray away from hiding covert data inside the data packet. Since covert data is never hidden directly inside the data packet, any attempt to extract data from the packet without knowing the algorithm first will not work.

The algorithm is designed to use a stream of packets originating from the sender and going to the receiver as a covert channel. If a packet stream is not available, the algorithm generates one which acts as a covert channel. Each packet in the stream is evaluated to see if a specific number of bits from target locations of its hash match the same number of bits of secret data. If they do match, the packet is marked and sent over the wire. The receiver sniffs traffic coming from the sender's machine and looks for the marked packets. Once they see the marked packet, the receiver creates the same hash of the marked packet and extracts the secret data bits from that packet and reassembles the covert data. The algorithm security is augmented by the addition of a moving target mechanism. The location of the bits that are evaluated in packet hash bits which are compared for every marked packet change. By moving the location of the bits that are evaluated, an attacker simply cannot guess the correct location and extract the covert data. They need to know the order of the bits that need to be evaluated from the packet hash and their specific location which renders a brute force attack useless. Additionally, since the packet is analyzed as a whole entity, statistical analysis does not yield anything because the packet is useless and doesn't convey any special meaning, except to the receiver. Figure 7 shows the steps the sender takes to hide data and send it to the receiver using the general algorithm.

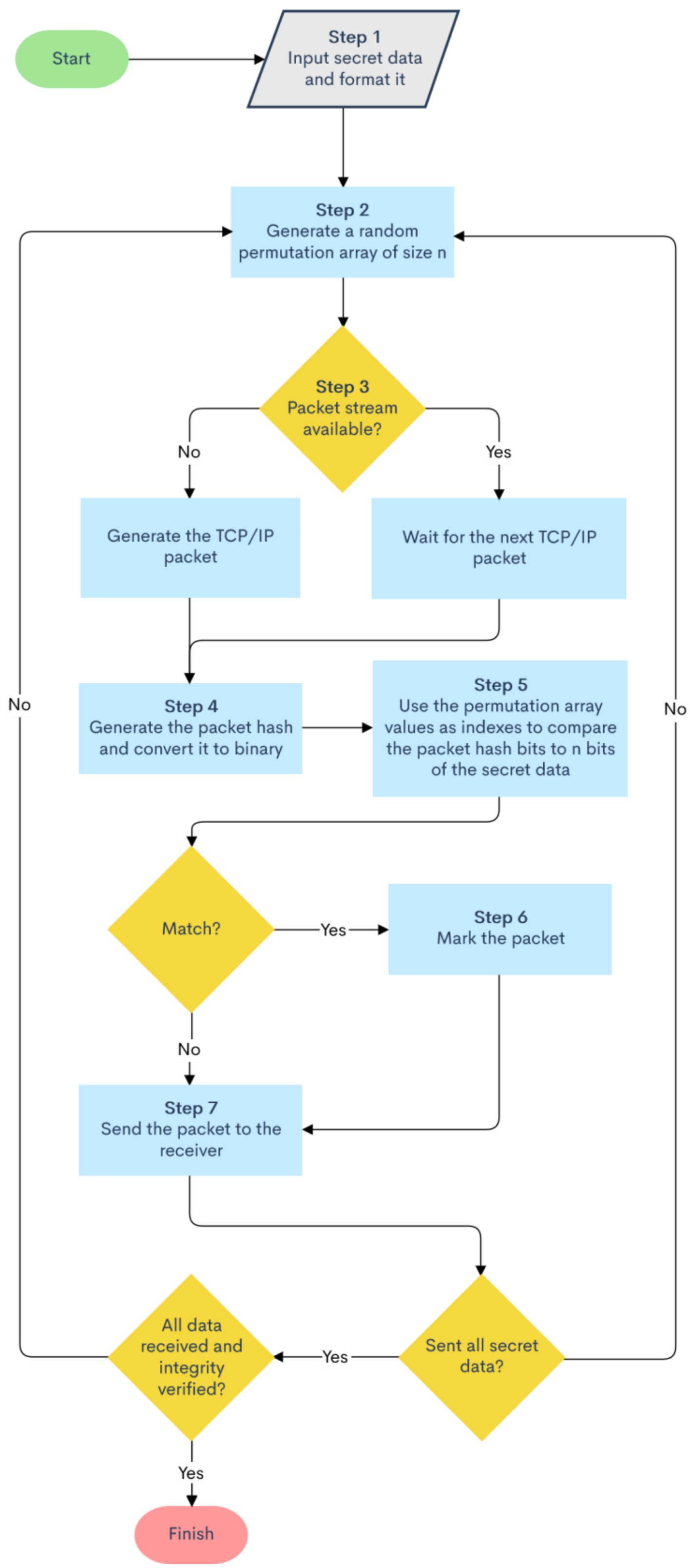


Figure 7. MTNS algorithm, sender side

The algorithm requires the sender and receiver to have pre-shared parameters. These parameters are the number of evaluation bits, a secret key, and a retry count. The number of evaluation bits identifies how many bits are intended to be hidden inside of a packet. It is the number of bits which are compared from the packet hash against the same number of covert bits. The value of the evaluation bits can range between 1 and up to including the size of the hash digest e.g. 256 for the SHA-256 hashing algorithm. The retry count specifies how many times the sender should send the message again if the receiver did not receive all the secret data or cannot verify the integrity of the secret data. The retry count is also used by the receiver to determine how many times they will keep sniffing for secret data from the sender if all the secret data was not received or the data integrity could not be verified.

The number of evaluation bits dictates the total time it takes to transfer the data and the number of bits that are transferred per packet. The higher the number of evaluation bits, the more data can be transferred per packet. On the other hand, as the number of evaluation bits increases, the total transmission time also increases because the algorithm needs to match a greater number of bits from the packet hash against the secret data. A larger amount of evaluation bits also provides more security from brute force attacks since an attacker would have to find the exact order of the permutation used when evaluating the packet hash. A smaller amount of evaluation bits allows the user to transfer data at a higher rate than if they used more evaluation bits because the algorithm is evaluating a smaller amount of positions from the packet hash against the secret data. The overall data transmission time is reduced when using a smaller amount of evaluation bits. By using a smaller amount of evaluation bits, the amount of data transferred is also smaller.

A smaller amount of evaluation bits provides less security than many evaluation bits because the number of positions from the packet hash that need to match the secret data are less. Nevertheless, smaller amounts of evaluation bits have their advantages. They are much faster in transferring data since the algorithm

The key is a shared secret between the sender and the receiver. The secret key allows the sender and receiver to prevent any third party from extracting secret data from the packets by acting as the seed for a random permutation generator which generates an array of values whose size is the same as the number of evaluation bits. Since both the sender and receiver have the same secret key, they generate the same sequence of permutation arrays.

Sender side. The first step of the general algorithm is taking in the secret data as input from the user. The secret data is then sent to the data formatter which generates the formatted message. The format of the message is the following: +<MSG> | <MSGCTR> |<First 4 chars and last 4 chars of SHA256(MSG+MSGCTR)>-. The formatted message begins with a + sign to indicate the start of a new message. Next, the actual plain text message is concatenated. The pipe (|) acts as a separator between each component of the formatted message. After the message, the message counter is attached. The message counter is used to keep track or of the order of messages that are sent by the sender to the receiver. The message counter will also be used in the reply the receiver sends to the sender acknowledging whether all the data was received, and if the integrity was verified or not. Preceded by another separator are the first four and the last four hexadecimal characters of the SHA256 hash of the message and the message counter. The sender sends over the first four and last four characters of the hash digest as an integrity verification mechanism. The receiver will compute the SHA256 hash of the on their end and compare the first four and last four hexadecimal characters to the provided characters. This is used to verify the message integrity by the receiver. After the message hash, a dash (-) is attached to signal the end of a message. This will let the receiver know that the sender has finished sending their message. Once the plaintext secret message has been formatted, the newly formatted message is then converted into binary for transmission.

The second step generates a random permutation array that is the same size as the number of evaluation bits. The values of the permutation array are limited to a range between 0 and the maximum size of the hash digest minus one (1), e.g., if the hash digest is 256 bits long, then the values in the permutation array will be between 0 and 255 inclusive. The permutation generator is seeded with the pre-shared secret key which allows the sender and receiver to generate the same permutation array for every marked packet. The values in the permutation array act as index locations of the binary packet hash that are to be checked against bits of secret data, n bits at a time, where n is the number of evaluation bits. For every marked packet, Alice and Bob generate a new permutation array, effectively moving or changing the target indexes to be evaluated against the next set of bits. By moving the locations of the evaluation bits, we make a brute force attack practically impossible for an attacker because they would have to find the correct location of the evaluation bits and process the evaluation in the correct order.

A point to note is that the permutation array need not be in increasing order. The values can be both in an increasing and decreasing order as determined by the permutation generator e.g. if the number of evaluation bits is equal to 8, the permutation array may look like this: [84, 22, 52, 12, 156, 194, 73, 2]. The non-linear order of the permutation array allows the algorithm to enforce order when comparing the binary packet hash bits against the covert data. In other words, the bits that are being checked aren't simply from left to right, their location can be all over the binary hash adding another layer of security.

The third step determines whether network traffic exists and can be used as a covert channel or not. If an existing channel doesn't exist, the sender generates a TCP/IP packet stream that can be used as a covert channel. If the TCP/IP packet stream is generated, the packet contains a randomly generated data which has no semantic meaning. The packet doesn't hold any semantic value and contains no secret information embedded inside either the TCP header, IP header, or data fields.

The fourth step generates the hash of the TCP/IP packet. The elements that are used as parameters for the hashing function are packet specific dynamic and non-dynamic values such as the source IP address, the destination IP address, source port number, the destination port number, the sequence number, and the data. This hash is then converted into its binary representation for step five.

The fifth step uses the permutation array values as indexes locations to compare the bits at those index locations in the binary packet hash with the first set of *n* bits of the secret data, where *n* is the number of evaluation bits. Figure 8 shows an example of step five. The number of evaluation bits is selected to be 8 and the range of the permutation values is between 0 and 255 (since SHA256 outputs a 256-bit hash value). The values of the packet hash in binary at the index positions, defined by the permutation array, are evaluated to see if they match the secret data in binary. If all the values match exactly with the secret binary data, then the algorithm marks the packet as defined in the next step. If the bits do not match exactly, then the algorithm skips the marking step and moves onto the next one after that.

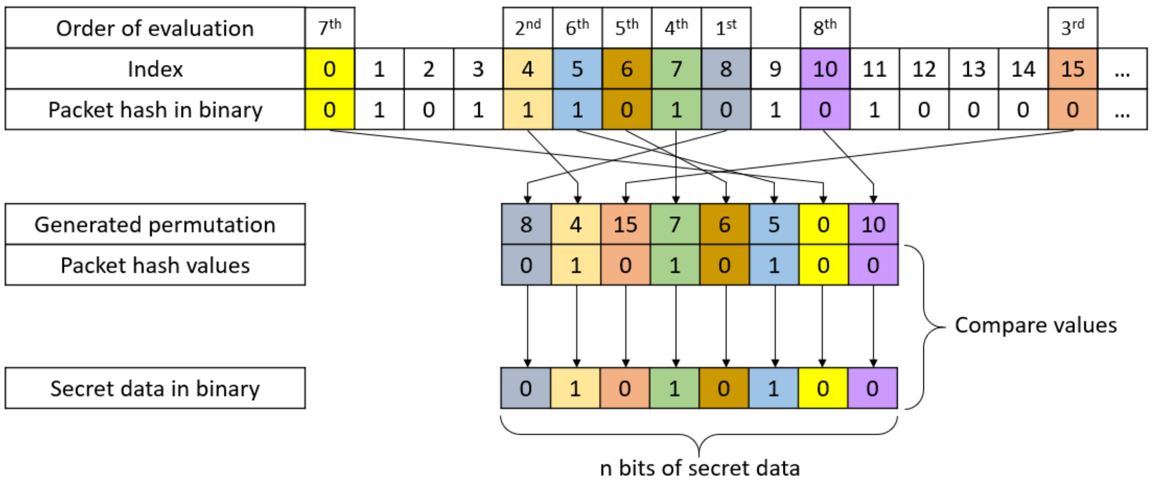


Figure 8. Evaluating the packet hash to see if it can hold covert data

Step six is about marking the packet. The marking of the packets tells the receiver that the packet "contains" *n* bits of secret data that need to be extracted. The marking includes the setting of the TCP push (PSH) flag in the TCP flag field. The aim is to use the traditional push flag to mark not the transmission of regular data, but also covert data. If the algorithm uses a stream of packets instead of generating one, the marking of the packets is not done by setting the push flag because packets in the stream might already have the push flag set. Therefore, finding a more covert way to mark packets is a part of the future work.

Step seven sends the packet with secret data to the receiver. Regardless of whether the packet is marked or not, it is sent to the receiver. After the packet is sent, the algorithm evaluates whether all the secret data has been sent. If all the data has been sent, the sender waits for an acknowledgement from the receiver. The acknowledgement from the receiver confirms that they received all the data and that it was unmodified by any third party. The data of the acknowledgement packet is the message counter which is used to keep track of the message order. If the receiver sends back a negative number as the acknowledgement data instead of the message counter, that means that the message wasn't properly received or verified by the receiver and that the sender should re-send the data. The sender will keep generating new permutations and sending the data and wait for the right acknowledgement response until the retry count threshold has been met or the receiver has received the data, whichever comes first. If the acknowledgement contains the message counter, the sender knows that all the data was received, and the integrity was verified therefore the process has finished.

Receiver side. Figure 9 shows the steps in the general algorithm from the receiver's side. The first step is to generate the same permutation array used by the sender which will be used to find the covert data in the following steps. Since both the sender and receiver know the scheme, and have the same secret key, the receiver uses it to seed the random permutation generator and creates a permutation array which is the size of the evaluation bits.

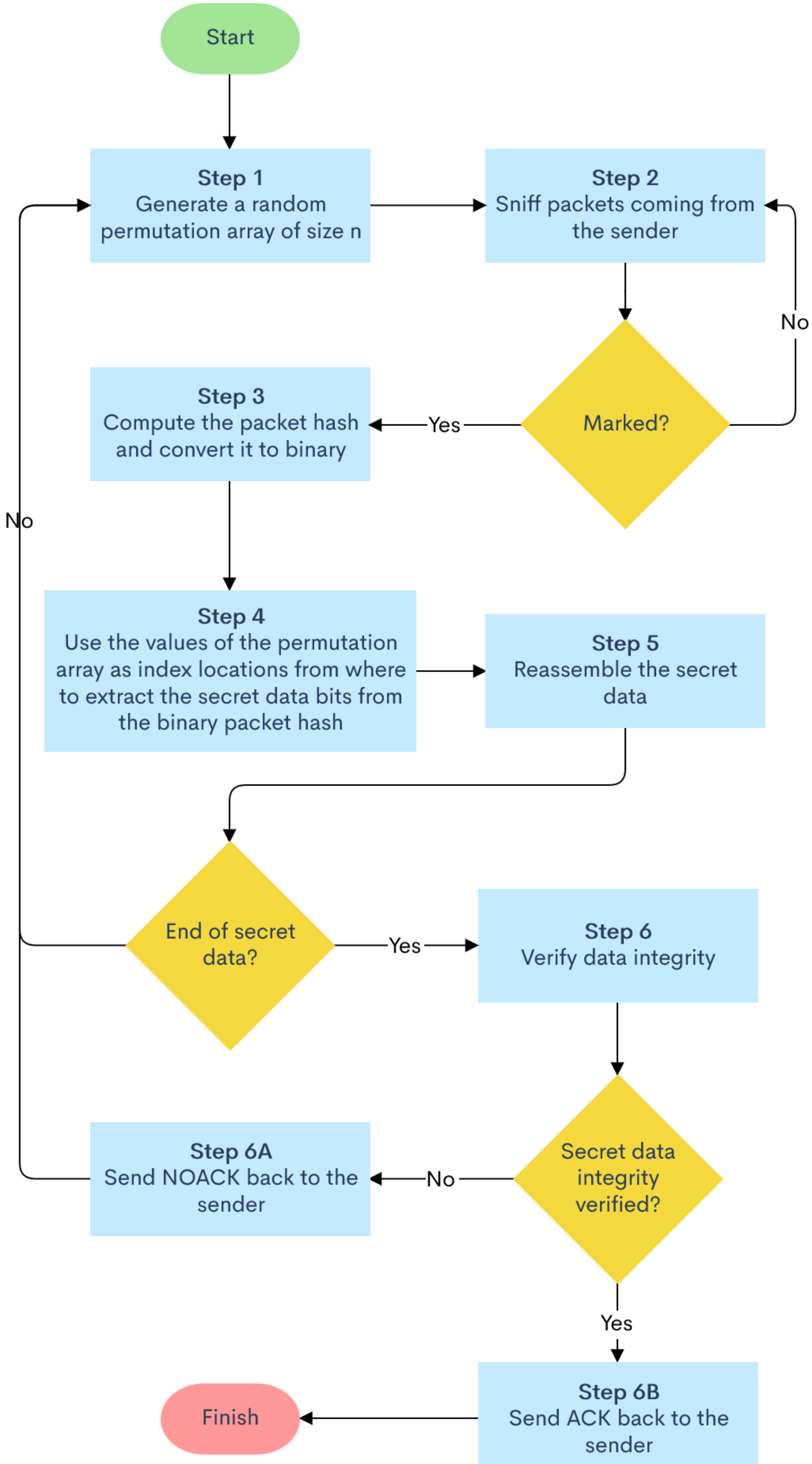


Figure 9. MTNS algorithm, receiver side

The second step is to monitor the traffic coming to receiver from the sender. The receiver is constantly monitoring the traffic for marked packets. If the receiver finds a marked packet, they move onto step three otherwise they keep monitoring the traffic until one is found.

In the third step, the receiver computes the hash of the packet using the same parameters that the sender used. The hash is then converted into binary which is where the covert data is stored. The fourth step extracts the secret data from the binary packet hash. This is done by reading the bits of the binary packet hash located at the indexes in the permutation array. Figure 10 shows how this is achieved.

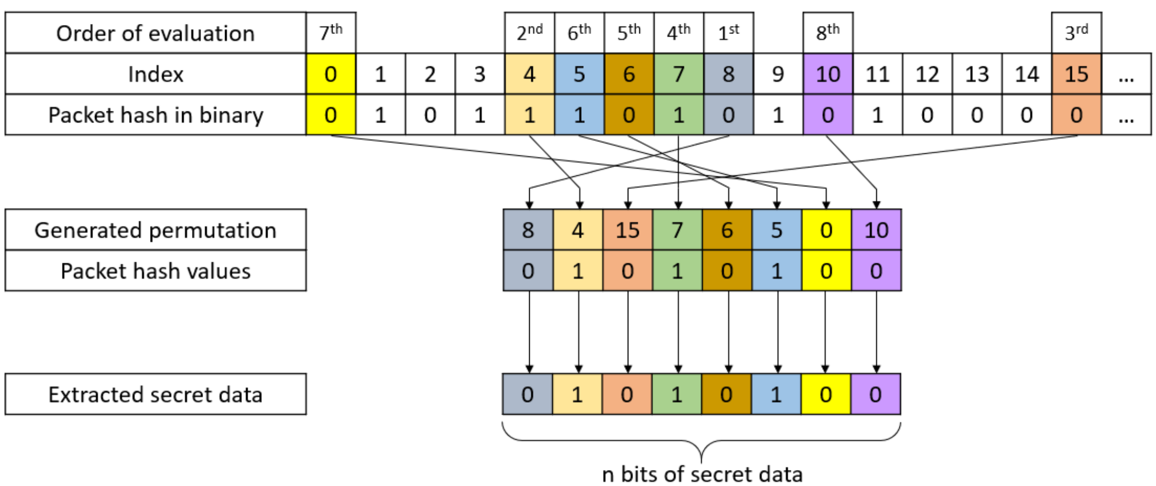


Figure 10. Extracting data from marked packets

Step five is the final step of the data extraction process. After the receiver has read the secret data from the packet, they reassemble the data into the complete binary string which contains all the secret data. When the receiver encounters the dash (-) as the covert data, they know that they sender has finished sending the data. If the receiver has not encountered the dash (-), they generate the next permutation array and keep sniffing for traffic.

Step six verifies the integrity of the data. The receiver calculates the SHA256 hash of the received message and then compares the first four and the last four hexadecimal characters of the hash to the provided hash. If they match exactly, then the receiver knows that the message was received completely and without alterations. If the message was received without any modifications, the receiver sends back an acknowledgement packet with the message counter as the data. If the message was altered in any way such that the computed hash did not match the provided hash, the receiver sends back a negative number to the sender indicating that the message was not received correctly and then proceeds to repeat the permutation array generation and the monitoring of traffic.

Proof of Concept

In the previous section, the general algorithm was outlined in detail and presented from both the sender and receiver's sides. In this section, a simplified version of the general algorithm is implemented as a proof of concept. The proof of concept does not contain the permutation mechanism, or the acknowledgement reply by the receiver but those can be easily added in future versions. For this section, the sender will be called Alice and the receiver will be called Bob.

The proof of concept is designed using two virtual machines. One virtual machine is the Alice computer and the other virtual machine is the Bob computer. Although a full duplex communication system is not implemented in the proof of concept, it is completely possible to create by letting Bob be the sender and Alice be the receiver. In that case, Bob would execute Alice's sender steps and Alice would execute Bob's receiver steps.

The virtual machines are deployed using Oracle VM VirtualBox [56], a free to use hypervisor designed to emulate many different types of operating systems. The operating systems on these two virtual machines are Ubuntu 18.04 LTS (Bionic Beaver) [57]. The proof of concept itself is developed using Python 3.8 [52] and uses the Scapy [59] packet crafting library. Figure 11 shows the network implementation of the proof of concept. Both virtual machines have two network interfaces enabled. The first interface, enp0s3, is enabled and used for an internal network. The internal network allows both virtual machines to communicate with each other in an isolated environment. This is the interface that is used for sending and receiving a packet stream generated by the algorithm that is used as a covert channel. The second interface, enp0s8, is enabled and used as a bridged adapter which allows the virtual machines to communicate directly with the Internet through the host machine. The enp0s8 interface is enabled for updating the software on the virtual machines and downloading new software packages.

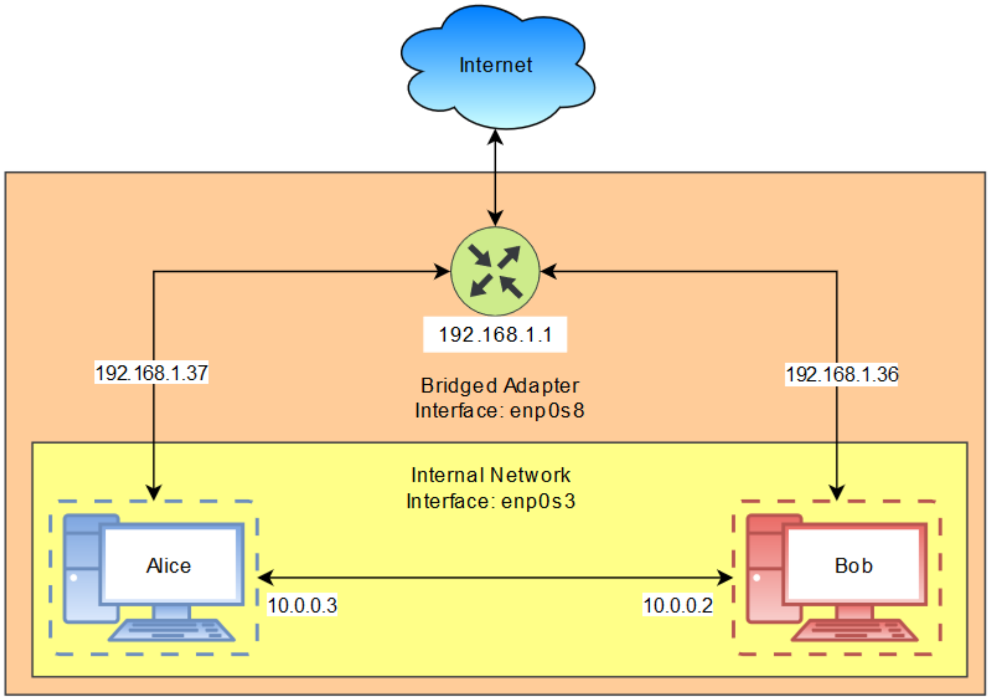


Figure 11. Proof of Concept network architecture

There are several parameters that Alice and Bob have pre-shared. They have each other's IP address, the port number to communicate through, the number of evaluation bits, and the secret key. The number of evaluation bits for the proof of concept must be between 8 and the maximum hash size of the hashing function (256 for SHA-256) and it must be a multiple of eight. The number of evaluation bits being restricted to multiples of eight is a design choice made for simplicity. One (1) ASCII [60] character is eight bits, therefore converting binary strings that have the size of a multiple of 8 to English characters is simple and straightforward. Of course, the proof of concept could be modified to use any number of evaluation bits between one and the size of the hash.

The following pseudo-code describes the proof of concept from the Alice's side:

1. *Take input from the user*
    a. *Create binary representation*
2. *Establish TCP connection with Bob on given IP address and port number*
3. *Create the TCP/IP packet with Scapy*
    a. *The PSH flag is set initially – marking the packet as containing data*
4. *Create the hash of the packet and convert it into binary*
    a. *Use the source IP address, destination IP address, source port number, destination port number, sequence number, and the data as parameters for the hashing function*
    b. *Convert the hash into binary*
5. *Compare the last 8 bits of the binary packet hash with 8 bits of the secret data*
    a. *Match?*
        i. *Send it to Bob*
    b. *No match?*
        i. *Remove the PSH flag and send it to Bob*
6. *Repeat steps 3-5 until the entire message is sent.*
7. *Ask user if they want to send more data*
    a. *Yes?*
        i. *Go to step 1*
    b. *No?*
        i. *Terminate TCP connection and exit*

Alice begins by taking input from the user. In this case, it is a string. She converts the string into its binary representation. Next, Alice creates a TCP session with Bob using the pre-shared port number and Bob's IP address. Alice then creates a TCP packet using Scapy. She initially sets the push flag, marking the packet as containing covert data. She will remove it later if the packet does not contain covert data. Next, she creates the hash of the packet using the SHA-256 hashing algorithm. The parameters of the packet that are used for the hash computation are the source IP address, destination IP address, source port number, destination port number, sequence number, and the data. These values are session and packet specific resulting in unique hashes for every packet created. Once the hash has been converted into its binary form, the last 8 bits (one ASCII character) of the binary packet hash are compared with 8 bits of the input from the user. If the binary packet bits match the bits of the input, then the packet is sent over the wire to Bob, already having the push flag set. If the bits do not match, then the push flag is removed and then the packet is sent over the wire to Bob. Alice repeats the steps of creating packets, generating the hashes, and comparing the bits until all the covert data is sent to Bob. If Alice wants to send more data, she has that option once all the previous data has been sent.

The following pseudo code describes the proof of concept from the receiver (Bob) side:

1. *Establish TCP session with Alice on given IP address and port number*
2. *Sniff traffic coming from Alice's machine*
3. *When marked PSH flag is found*
    a. *Create the packet hash and convert it to binary*
        i. *Use the source IP address, destination IP address, source port number, destination port number, sequence number, and the data as parameters for the hashing function*
    b. *Extract the secret data bits which are the last 8 bits of the binary packet hash*
    c. *Re-assemble the data*
4. *Repeat until Alice stops sending data*

Bob's steps are much simpler than Alice's steps since he is simply reading the covert data in the marked packets. He begins by establishing a TCP connection with Alice's machine using her IP address and the mutual port number used to communicate. Next, he continuously sniffs for traffic coming from her machine on the specific port. When he sees a packet with the push flag set, he generates the same hash using the source IP address, destination IP address, source port number, destination port number, sequence number, and the data as parameters for the hashing function. After converting the hash into its binary representation, Bob reads the last 8 bits of data and reassembles the covert message. Bob repeats the steps of sniffing for marked packets, generating the binary packet hash, and reading the last 8 bits until Alice stops sending him data.

It is important to note that the goal of the proof of concept was to determine if the algorithm could be implemented. Therefore, a version of the general algorithm was implemented which contained the core functionality of the algorithm by abstracting the embedding of data inside the data packets using hashing. Future versions of the proof of concept could include the moving target functionality of the permutation array and a mechanism for determining if Bob received the message completely and without any alterations. Another feature that could be included in future versions of the proof of concept is a duplex communication system where both Alice and Bob can send messages instead of only Alice being able to send messages. This two-way communication would make the proof of concept more robust.

Results

Figure 12 shows the proof of concept in action from Alice's side. Figure 13 shows the proof of concept from Bob's side. Alice is sending the secret message "hello" to Bob by evaluating the last eight bits of the packet binary hash. Bob is sniffing for marked packets, extracting the last eight bits of the marked packet binary hash, and rebuilding the secret message letter by letter.

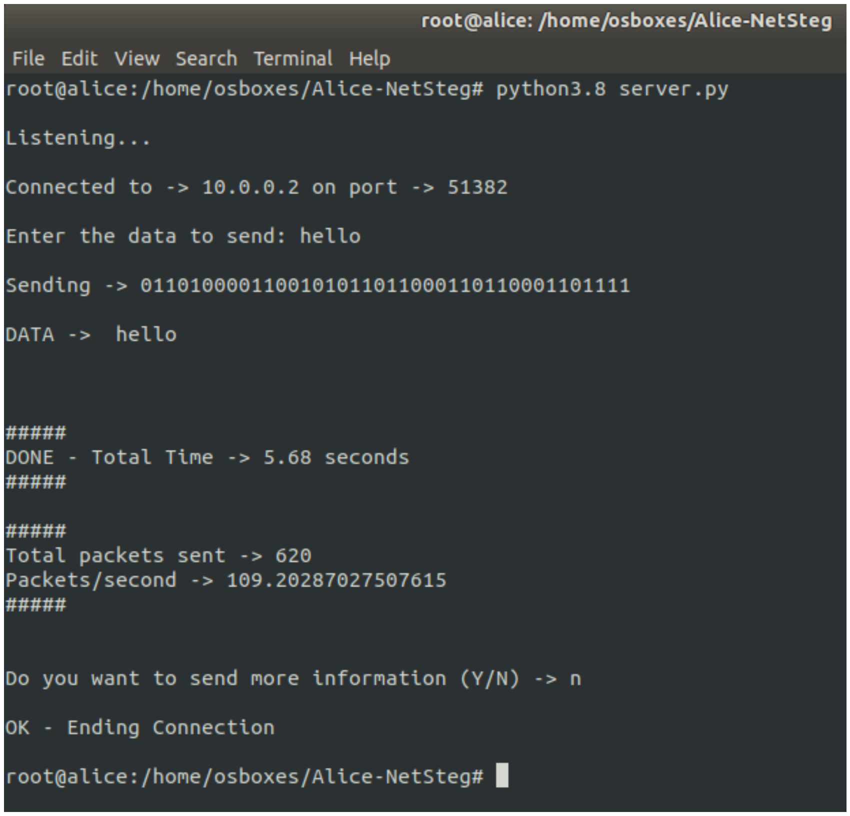


Figure 12. Sending data from Alice's side

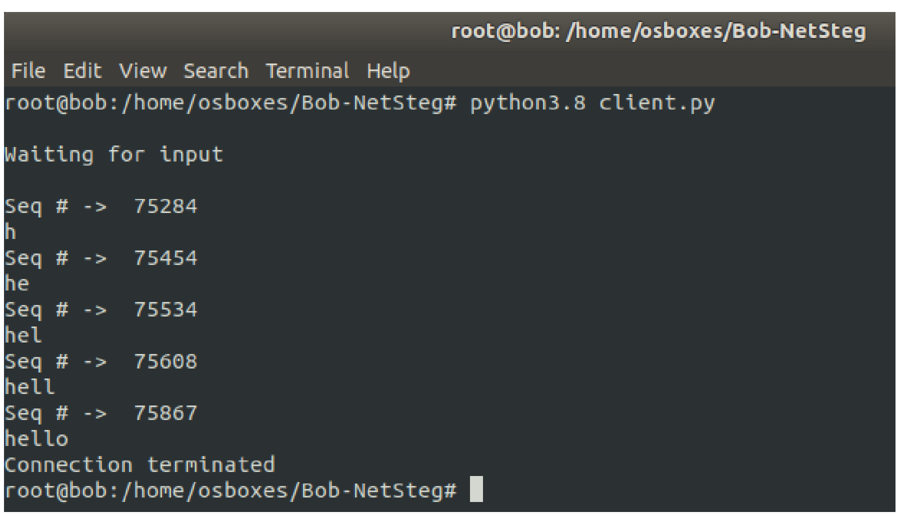
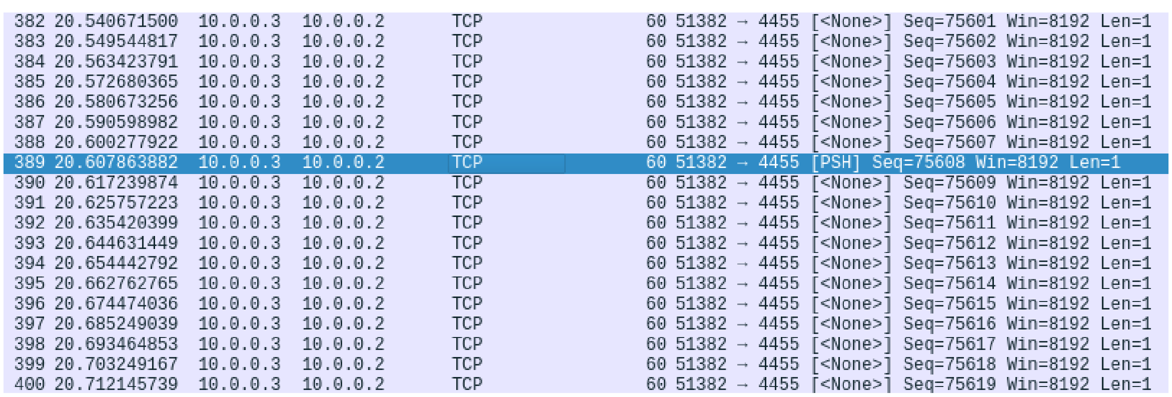


Figure 13. Receiving data from Bob's side

Wireshark [61], a network sniffer, is used to monitor the data transfer between Alice and Bob’s virtual machines. Figure 14 shows the Wireshark output of the data transfer between Alice and Bob. A push flag packet is highlighted. By correlating the sequence number from the Wireshark packet capture with figure 13, the packet contains the second “l” in “hello”. Figure 15 shows the contents of the packet highlighted in figure 14. Wireshark allows the user to view each layer of the packet, the data, and provides additional analysis information about the packet. A point to note is that the data is random data. It is a random number generated by the proof of concept. It doesn’t convey any special meaning. Another point to note is that the proof of concept supplied the source IP address, destination IP address, source port number, destination port number, the sequence number, the push flag, and the data. The rest of the fields for the packet were filled automatically by Scapy.



382	20.540671500	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75601 Win=8192 Len=1
383	20.549544817	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75602 Win=8192 Len=1
384	20.563423791	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75603 Win=8192 Len=1
385	20.572680365	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75604 Win=8192 Len=1
386	20.580673256	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75605 Win=8192 Len=1
387	20.590598982	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75606 Win=8192 Len=1
388	20.600277922	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75607 Win=8192 Len=1
389	20.607863882	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [PSH] Seq=75608 Win=8192 Len=1
390	20.617239874	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75609 Win=8192 Len=1
391	20.625757223	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75610 Win=8192 Len=1
392	20.635420399	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75611 Win=8192 Len=1
393	20.644631449	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75612 Win=8192 Len=1
394	20.654442792	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75613 Win=8192 Len=1
395	20.662762765	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75614 Win=8192 Len=1
396	20.674474036	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75615 Win=8192 Len=1
397	20.685249039	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75616 Win=8192 Len=1
398	20.693464853	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75617 Win=8192 Len=1
399	20.703249167	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75618 Win=8192 Len=1
400	20.712145739	10.0.0.3	10.0.0.2	TCP	60	51382 → 4455 [<None>] Seq=75619 Win=8192 Len=1

Figure 14. Wireshark packet capture

```
▸ Frame 389: 60 bytes on wire (480 bits), 60 bytes captured (480 bits) on interface 0
▸ Ethernet II, Src: PcsCompu_d7:54:2b (08:00:27:d7:54:2b), Dst: PcsCompu_d7:54:2b (08:00:27:d7:54:2b)
▾ Internet Protocol Version 4, Src: 10.0.0.3, Dst: 10.0.0.2
    0100 .... = Version: 4
    .... 0101 = Header Length: 20 bytes (5)
  ▸ Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
    Total Length: 41
    Identification: 0x0001 (1)
  ▸ Flags: 0x0000
    Time to live: 64
    Protocol: TCP (6)
    Header checksum: 0x66ca [validation disabled]
    [Header checksum status: Unverified]
    Source: 10.0.0.3
    Destination: 10.0.0.2
▾ Transmission Control Protocol, Src Port: 51382, Dst Port: 4455, Seq: 75608, Len: 1
    Source Port: 51382
    Destination Port: 4455
    [Stream index: 0]
    [TCP Segment Len: 1]
    Sequence number: 75608
    [Next sequence number: 75609]
    Acknowledgment number: 0
    0101 .... = Header Length: 20 bytes (5)
  ▾ Flags: 0x008 (PSH)
      000. .... .... = Reserved: Not set
      ...0 .... .... = Nonce: Not set
      .... 0... .... = Congestion Window Reduced (CWR): Not set
      .... .0.. .... = ECN-Echo: Not set
      .... ..0. .... = Urgent: Not set
      .... ...0 .... = Acknowledgment: Not set
      .... .... 1... = Push: Set
      .... .... .0.. = Reset: Not set
      .... .... ..0. = Syn: Not set
      .... .... ...0 = Fin: Not set
      [TCP Flags: ········P···]
    Window size value: 8192
    [Calculated window size: 8192]
    [Window size scaling factor: -1 (unknown)]
    Checksum: 0x4860 [unverified]
    [Checksum Status: Unverified]
    Urgent pointer: 0
  ▸ [SEQ/ACK analysis]
  ▸ [Timestamps]
    TCP payload (1 byte)
▾ Data (1 byte)
    Data: 32
    [Length: 1]

0000  08 00 27 d7 54 2b 08 00  27 d7 54 2b 08 00 45 00   ··'·T+·· '·T+··E·
0010  00 29 00 01 00 00 40 06  66 ca 0a 00 00 03 0a 00   ·)····@· f·······
0020  00 02 c8 b6 11 67 00 01  27 58 00 00 00 00 50 08   ·····g·· 'X····P·
0030  20 00 48 60 00 00 32 00  00 00 00 00                ·H`··2· ····
```

Figure 15. Contents of a marked packet

Chapter 4

Analysis

Probability

In this section the section, the algorithm is analyzed for the probability of an attacker managing to uncover the secret data. A sample scenario is defined where the number of evaluation bits, denoted as *n*, is 8 bits. Both the sender and receiver have secret keys which they are using to generate permutation arrays. The secret data is "Hello", and the packet transmission rate is 100 packets per second, and the general algorithm is known to the attacker.

The algorithm keeps creating new packets and calculates their hashes until the bits located at the indexes defined by the permutation array match *n* bits of covert data. The maximum number of possible *n*-bit binary strings that can be created is 2^n since each position can have two possible values, like the following: $2_1 \times 2_2 \times \cdots 2_n = 2^n$. Since *n* is 8 in this scenario, the maximum number of possible 8-bit binary strings that can be created is 2^8 or 256. That means, in the worst case, the algorithm must calculate 256 hashes before finding a match to 8 bits of secret data (assuming that the 8-bit strings are unique for every consecutive calculation and do not repeat). The probability of matching one unique string out of the maximum calculated hashes is $\frac{1}{2^n}$ which, for this scenario, is $\frac{1}{256}$. That means that Alice has the probability of $\frac{1}{256}$ of matching 8 bits of the packet hash to 8 bits of the secret data. If the attacker knew the implementation of the algorithm, all they must do is read the eight bits of the marked packet hash to extract the secret data. The burden of probability falls on the sender.

Therefore, using static bit locations e.g. the last eight locations of the packet hash, is a bad idea. The solution to this problem is moving the locations, i.e. moving the target. This is where the permutation array comes into effect. The permutation array, as discussed before, is a randomly generated array of values of size *n* in which the order of the values is enforced. The order property of a permutation is important in adding security to the algorithm because the algorithm must compare and read values in a specified order determined by the array preventing a right to left data extraction event, adding more security. Since the range of values is between 0 and the size of the hash - 1, in this scenario, the random permutation generator creates a permutation array of size *n* with values ranging between 0 and 255 inclusive (256 total possibilities). Selecting a permutation of 8 values from 256 values yields 16,517,640,193,528,320,000 possible combinations. If the *n* is increased, the possible number of permutations increases exponentially, e.g., if *n* is 16, the possible number of 16 permutations out of 256 is 210,875,602,102,456,269,086,537,616,669,081,600,000 and if *n* is 24, the possible number of 24 permutations out of 256 increases to 2,063,062,690,012,022,711,962,604,920,118,953,278,227,813,467,422,720,000,000.

The Summit supercomputer [62], the fastest supercomputer in the United States, can perform a maximum of two hundred quadrillion calculations per second [63]. It would take the Summit supercomputer 82.58 seconds running at maximum capacity to calculate all the 16,517,640,193,528,320,000 different permutations. If the number of evaluation bits is increased to the next multiple of eight, 16 bits, then it will take the

Summit supercomputer 1.05×10^{21} seconds to make its way through 210,875,602,102,456,269,086,537,616,669,081,600,000 permutations. Since the permutations are generated via a random number generator which is seeded with the shared secret key, even if the attacker knows every single detail about the implementation and the algorithm, they cannot recreate the specific permutation used to evaluate *n* bits of secret data without the key. Also, since the permutation changes for every *n* bits of data, the attacker has a very short time to guess the create the permutation array before it changes.

Parameters used in the probability analysis and later in the data transfer analysis are show in Table 2.

Table 2

Probability and data transfer equation parameters

Variable	Value
w	Size of the hash
s	Size of the permutation
n	Number of evaluation bits
p	Transmission rate in packets per second
y	Data transfer rate in bits per second
q	Data to transfer in bits

The probability of the attacker correctly guessing the permutation indexes is defined in Equation 1:

$$\text{P(Correct permutation)} = \frac{1}{\frac{w!}{(w-s)!}} = \frac{(w-s)!}{w!} \quad (1)$$

Using equation 1, in the scenario where *n* and *s* are 8 respectively and *w* is 256, the probability of the attacker finding the correct permutation is the following:

$$\text{P(Correct permutation, where } n = s = 8 \text{ \& } w = 256) = \frac{(256-8)!}{(256!)}$$

$$\text{P(Correct permutation, where } n = s = 8 \text{ \& } w = 256) = 6.05 \times 10^{-20}$$

The attacker must know the secret key to generate the correct permutation in the correct order. Without the secret key, the attacker cannot generate the correct permutation which tell them in which order the bits are evaluated, and therefore cannot read the secret data.

Performance

In this section, the performance of the general algorithm and the implementation is analyzed. Equation 2, the data transfer equation is introduced and discussed. Results of timing measurements are also analyzed. The performance of a covert channel is important to measure because it is used to determine how dangerous a covert channel is. Any covert channel with a rate greater than one bit per second can be considered a high-rate covert channel [64].

Theoretical performance. The theoretical performance of the general algorithm is determined by the probability of matching *n* bits of the binary packet hash located at the permutation indexes with *n* bits of secret data along with the packet transmission rate between the sender and the receiver. The time it takes to create the TCP/IP packet, generate a permutation, compare the bits, and other minutia in the algorithm and proof of concept are not considered in the theoretical performance calculations. Equation 2 describes the data transfer equation:

$$\text{P(Matching } n \text{ bits of the binary packet hash with } n \text{ bits of covert data)} = \frac{1}{2^n}$$

$$\text{Total possible packets per second based on } p = n\,\frac{bits}{packet} \times p\,\frac{packets}{second}$$

$$\frac{1}{2^n} \times \left[n\,\frac{bits}{packet} \times p\,\frac{packets}{second}\right] = y\,\frac{bits}{second}$$

$$\text{Total seconds to transfer } q \text{ bits of information} = T_s = \frac{q\ bits}{y\,\frac{bits}{second}}$$

Therefore:

$$T_s = \frac{q\ bits}{\frac{1}{2^n} \times \left[n\,\frac{bits}{packet} \times p\,\frac{packets}{second}\right]} \qquad (2)$$

By multiplying the probability of having one *n* bit match per packet by the total possible packets that are being sent per second, the number of possible bits per second, *y*, is derived based on the number of evaluation bits, *n*, and a packet transfer rate *p*. For the example scenario, *n* is 8, *p* is 100 packets per second, and the data to send is “Hello” which is 40 bits of information.

First, the bits per second rate must be calculated:

$$\frac{1}{2^8} \times \left[8\ \frac{bits}{\cancel{packet}} \times 100\ \frac{\cancel{packets}}{second}\right] = 3.125\ \frac{bits}{second}$$

Based on the denominator of equation 2, the algorithm evaluating 8 bits of data per packet transferring packets at 100 packets per second can transfer 3.125 bits per second which is about three times greater than the 1 bit per second high covert channel benchmark [2].

$$T_s = \frac{40\ \cancel{bits}}{3.125\ \frac{\cancel{bits}}{second}} = 12.8\ seconds$$

Using equation 2, transferring 40 bits of data at a rate of 3.125 bits per second will take 12.8 seconds.

Experimental performance. To get an accurate representation of how the proof of concept's run times compared with the theoretical calculations, 26 trials were conducted, each trial running 100 times resulting in a total of 2600 total proof of concept runs. The amount of data for every consecutive trial was increased by 8 bits, starting with the letter "a" (8 bits) and ending with the entire alphabet "abcdefghijklmnopqrstuvwxyz" (208 bits). Two sets of 26 trials were ran with a controlled packet transmission rate, 75 packets per second and 100 packets per second respectively. The third set of 26 trials were ran with transmission rates controlled by the operating system, i.e., no packet rate limitations were applied, the system determined how fast the packets were transmitted between the virtual machines.

Figures 16 - 18 show the theoretical times compared to the simulated times. The theoretical time (orange line), calculated using equation 2 described in the previous section, increases in a linear fashion with every 8 bits of data that is added. The simulated time (blue line), measured from the proof of concept, also increases linearly, closely following the points of the theoretical times. The slight differences in the theoretical and simulated times are due to the implementation of the proof of concept and the virtual machine environment. The Alice and Bob virtual machines are hosted on a Windows 10 PC. The PC must divide its resources between the host operating system and the two virtual machines. Some sluggishness in the processing capability is to be expected due to the division of processor power, RAM, and storage. Even with the expected slower computational speed of the virtual machines, the simulated times are very similar to the theoretical times.

Equation 2 can be used to calculate the average time in seconds the algorithm will take to send q bits of information, with a transfer rate of p packets per second, while evaluating n bits of data per packet. Figure 18's transmission rate is set by the operating system of the virtual machine; therefore, the times are not increasing linearly. The operating system is determining the transmission rate for each trial and that is why the times are fluctuating more than figures 16 and 17. Nevertheless, equation 2 still holds in figure 18 because the algorithm is the same, the only difference is that the transmission time is determined by the operating system instead of the user.

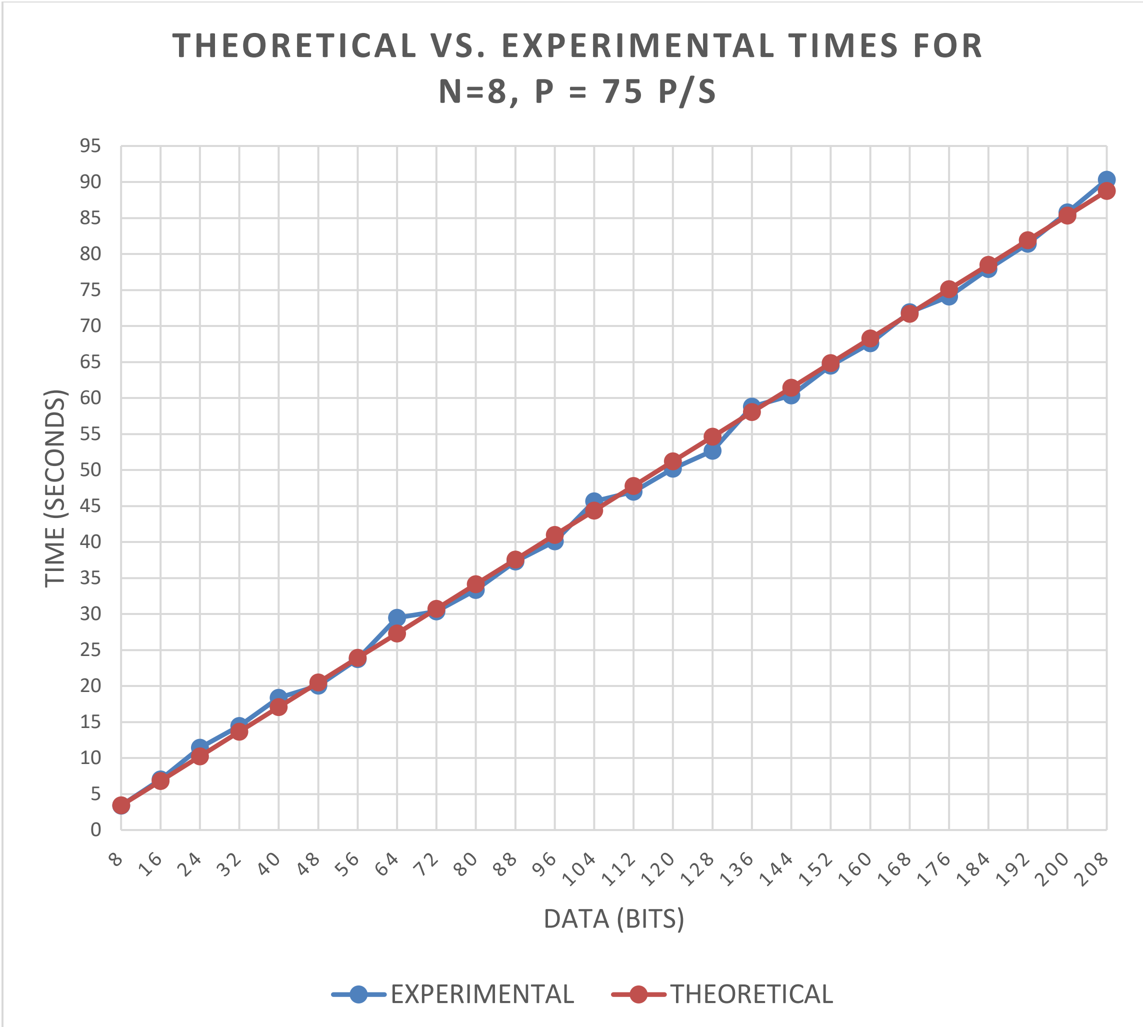


Figure 16. Theoretical vs. experimental run times for n = 8, and p = 75 p/s

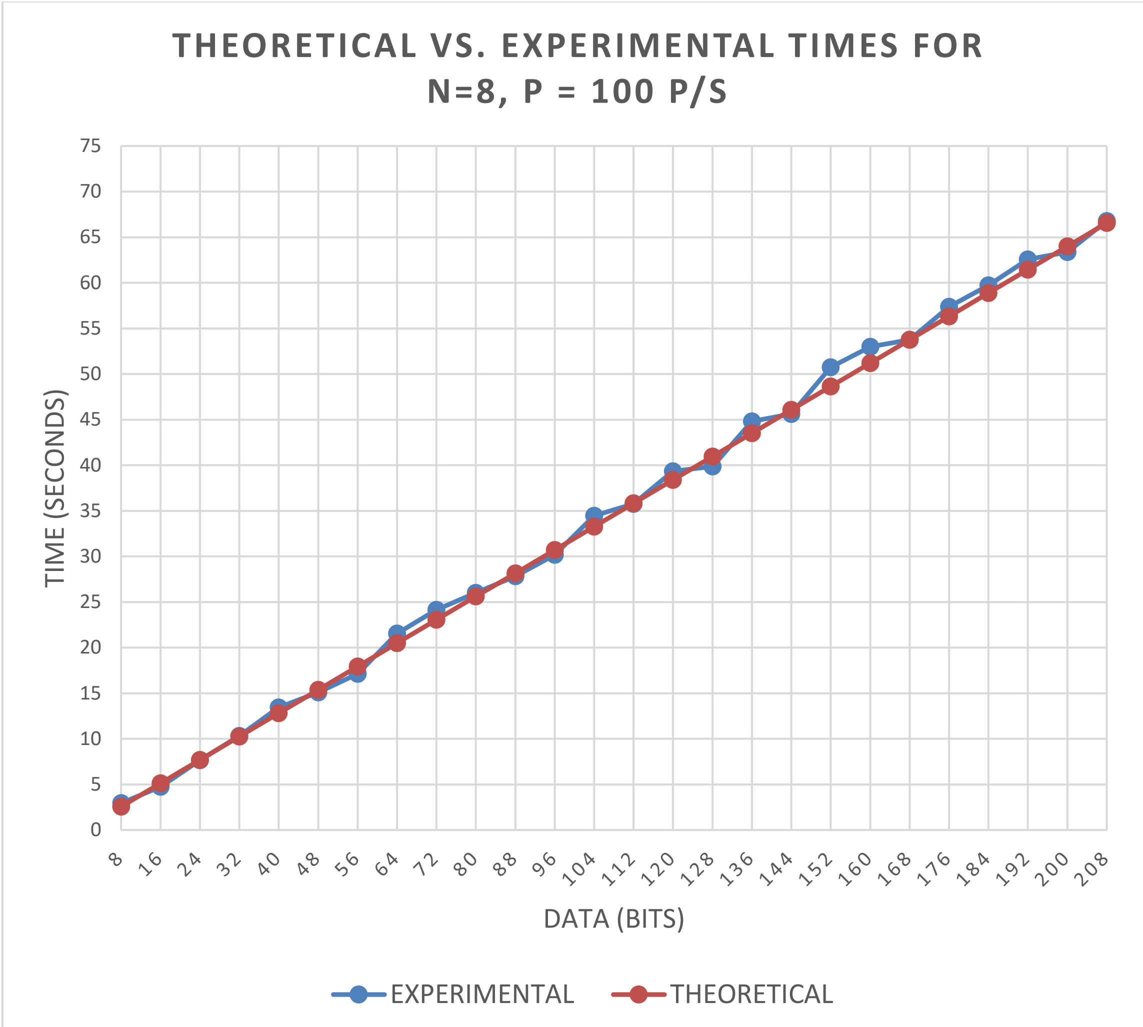


Figure 17. Theoretical vs. experimental run times for n = 8, and p = 100 p/s

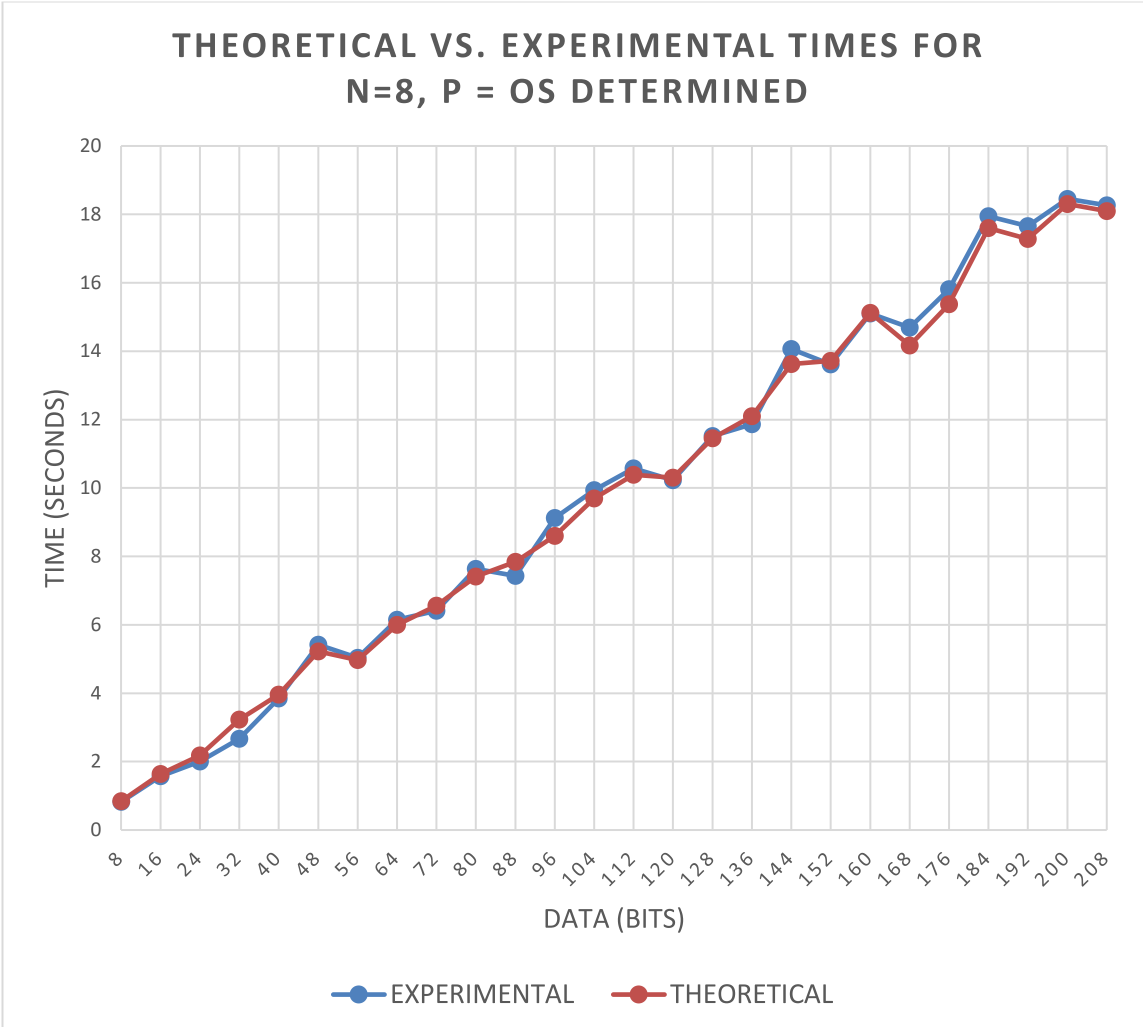


Figure 18. Theoretical vs. experimental run times for n = 8, and p = variable p/s

Figures 19 - 21 show the average packet transfer rates. The packet transfer rates for each run are collected by taking the average of the 100 runs' individual packet transfer rates. Controlling the packet transfer rate is done by implementing a slight delay between sending packets. An automatic transmission rate correction feature was implemented in the proof of concept which would increase or decrease the interval of time between the packets based on the transmission rate of each run in the trial. The simulated packet transfer rates are very close to packet transfer rates used for the theoretical time calculations. The minor fluctuations are due to numerous mechanisms such as internal program delays, operating system delays, and transmission delays. Figure 21 shows the average packet transfer rate of the trial where the transfer rate is handled by the system. There is a large variance in transfer rates from 290 packets per second to 375 packet per second because the virtual machine operating systems determined the transmission speed for each trial. Additionally, there are many variables that the operating systems decides on that contributes to the fluctuations in the packet transmission speed. Equation 2, the data transfer equation, still holds in this scenario because each run's transfer time is calculated with its specific transmission rate instead of a set transmission rate.

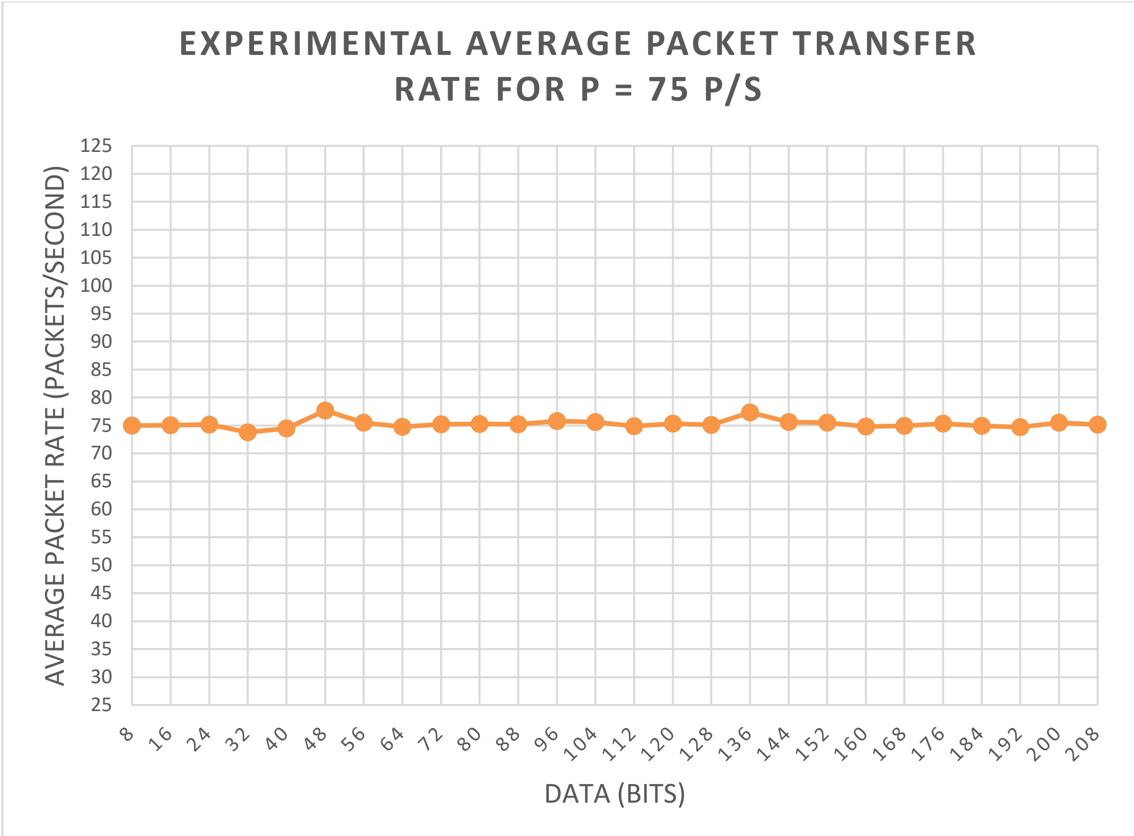


Figure 19. Average packet transfer rates for p = 75 p/s

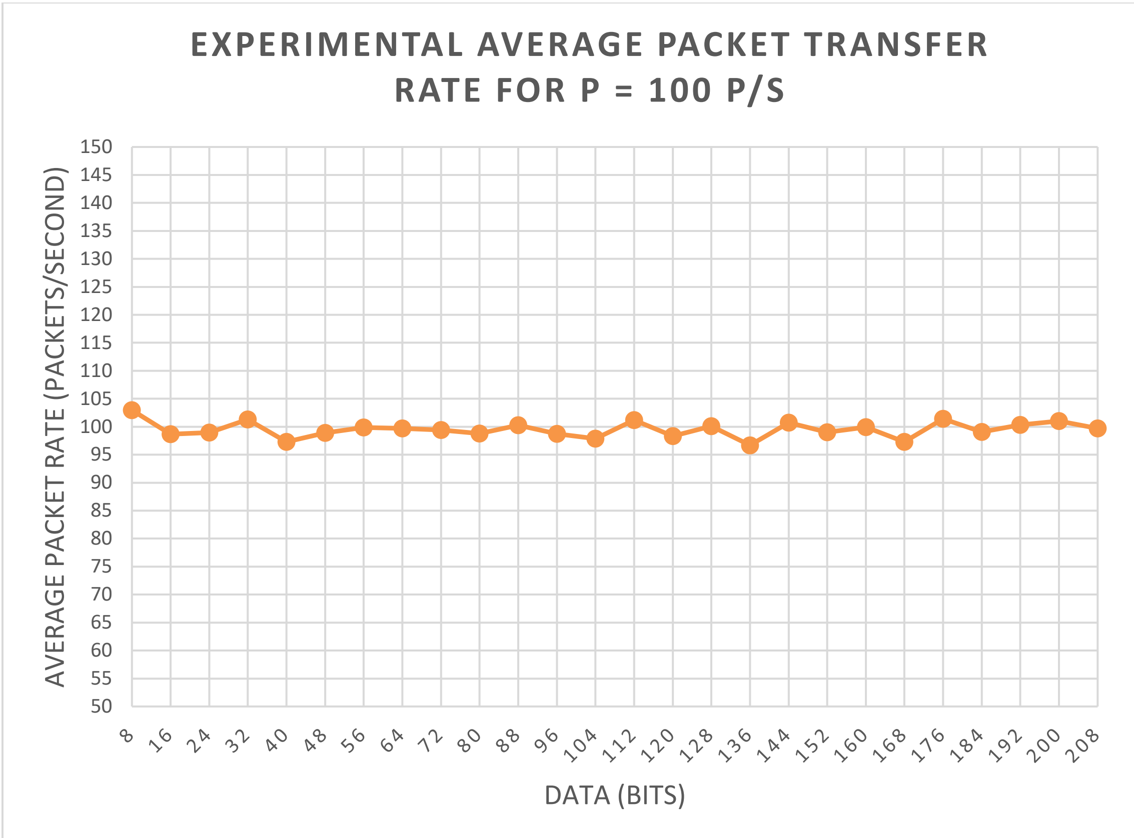


Figure 20. Average packet transfer rates for p = 100 p/s

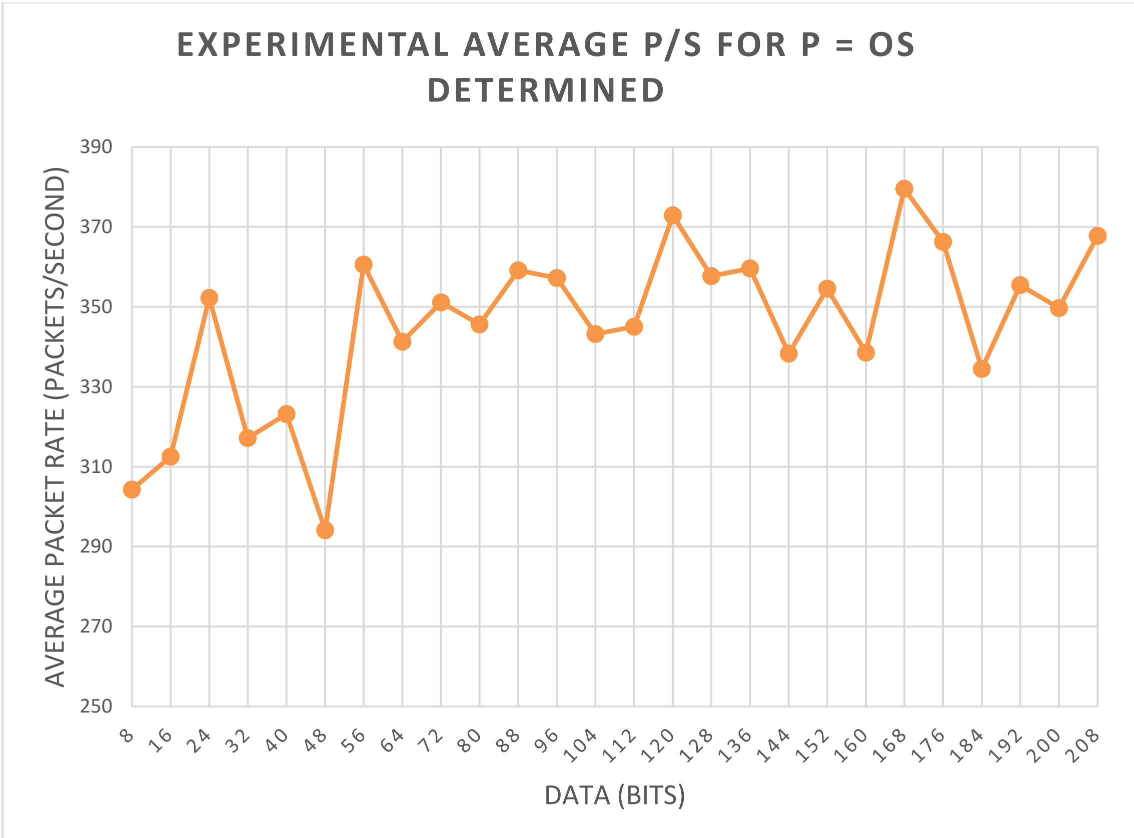


Figure 21. Average packet transfer rates for *p* = variable p/s

Figure 22 shows an interesting relationship between the packet transfer rate and the time it takes to transfer 208 bits of information at those packet transfer rates. The time to complete the transmission is logarithmically decreasing the higher the packet rate is. The fastest average packet rate for the proof of concept was 379 packets per second using virtual network interfaces. Business and enterprise grade routers and networking equipment can send many more packets per second than 379 thus increasing the bandwidth of the scheme and allowing the sender to increase the amount of data sent while reducing the transmission time. Equation 2 will still hold in these cases regardless of the transmission speeds because the algorithm being used is still the same and relies on the probability of the packet hash matching *n* bits of the secret data and the transmission speed of the data packets.

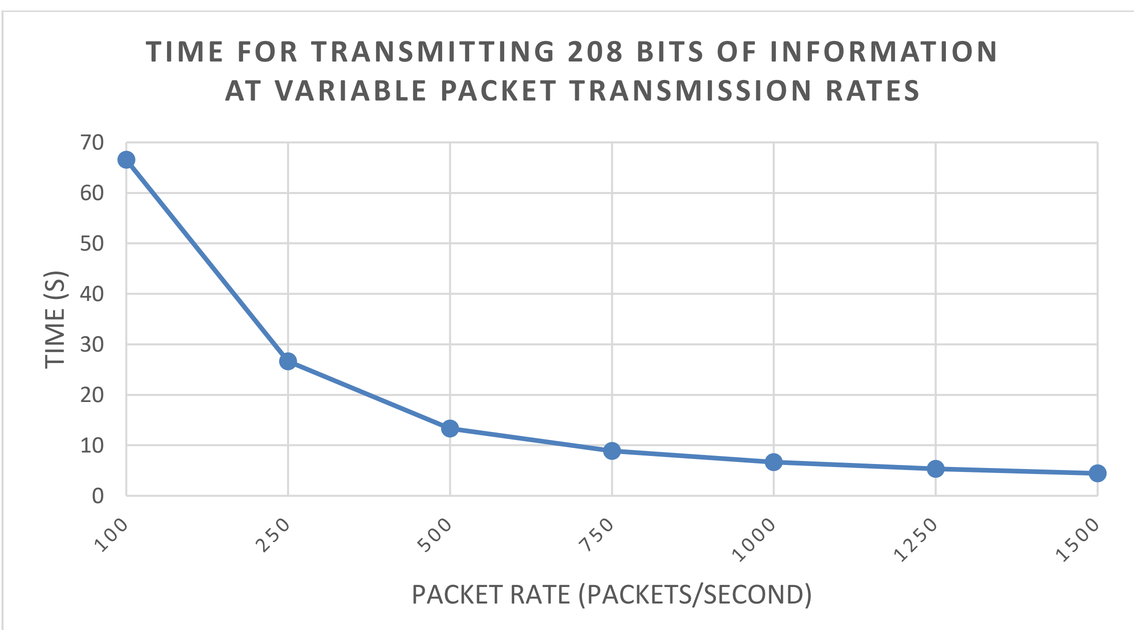


Figure 22. Times for transmitting 208 bits of data

Detectability and Mitigation

No network steganography method is completely secure. The following is a detectability and mitigation analysis of the general algorithm. Steganalysis is the process of detecting the presence of and ultimately extracting covert data from a carrier [65] [66]. There is one way that the scheme could be exposed. It is important to note that since the "embedding" of covert data happens by comparing indexes of the packet hash with covert data, the covert data is never stored inside a packet. The packet represents covert data and without the appropriate key and the correct permutation, it is nearly impossible to extract the covert information so even if the scheme is discovered, the warden is not able to read the data.

The way to detect if a covert channel is being used is by the marking of the packet. The mark tells the receiver which packets have hidden information. The general algorithm describes that the marking of the packets is was done with the TCP push flag, if it generates a custom packet stream, which is used to push data from the user to the receiver [24]. If the general algorithm uses an already available packet stream, the marking scheme is left for future research. If the warden realizes that the push flag is used to send data other than what's in the data portion, i.e. covert data, he can shut down the channel. But since the push flag is described by the TCP standard to be used when sending data, the warden cannot differentiate whether covert data is also being sent in addition to the plaintext data.

If the warden is an active warden, he can manipulate the fields of the packet and change the values. A point to note is that an active warden is akin to a man in the middle who has total control over the network channel. The only way to stop an active warden is to prevent them from detecting the covert channel in the first place. Since no covert data is hidden inside the protocol, the two ways to mitigate this covert channel are to change the values that are used to calculate the hash (source IP address, destination IP address etc.) or to stop the communication channel entirely. Doing both will result in performance loss between the sender and the receiver and may not be worth it for network administrators since closing the communication channel is the same as shutting off the Internet for that process, and changing the contents of packet may have negative effects on legitimate processes.

Chapter 5

Conclusion and Future Work

Conclusion

The field of information hiding is a broad field with many different techniques used daily to keep information hidden and away from prying eyes. One of those techniques is network steganography. Network steganography is a branch of information hiding that uses network protocols as information carriers to hide and transmit covert information. The widespread adoption of the Internet, and its open system architecture make it an attractive candidate for information hiding. Two types of network steganography exist, storage channel and timing channel. Storage channel network steganography is a class of network steganography where the field values of protocol are manipulated to transmit secret data. Timing channel network steganography is a class of network steganography that modifies the timing of the events in a carrier to transmit secret data. Storage channel network steganography is more prevalent because it is easier to implement, allows for more control over the protocol, and there are many different protocols in the TCP/IP protocol suite.

Many of the current approaches to storage channel network steganography suffer from a low transmission rate and the vulnerability of hiding covert data inside the protocol header and data fields. If the covert channel is discovered, the covert data can be read which is the ultimate breach of confidentiality. A new type of storage channel network steganography is introduced. It allows packets to represent the covert data instead of hiding it directly inside the packet. This new approach does not hide data inside the packet but instead allows the receiver to re-create data out of data packets using a holistic packet evaluation algorithm. The algorithm utilizes hashing to create a unique signature of the packet and compares values from the hash to values of the secret data. If they match, then the packet is marked and sent to the receiver. The receiver creates the same signature of the marked packet and extracts the data from the packet hash. Additional security is added to the algorithm in the form of a moving target mechanism which changes the locations from which the data in the packet hash is evaluated. By implementing the moving target functionality, brute forcing the algorithm is impossible since the location is changing for every marked packet and the permutations are generated via a random permutation generator that is seeded with the shared secret key. Controlling the transmission rate of the packets and increasing the number of evaluation bits allows for increased transfer bandwidth.

A proof of concept is developed to test the algorithm. Built using Python 3.8 and implemented on two virtual machines, the proof of concept implements a simplified version of the general algorithm. It creates a direct communication channel between the sender and receiver that is used as a covert channel. Different packet transmission speeds are tested to evaluate the accuracy of the simulated times against the theoretical times. The simulated times are identical to the theoretical times. A probability analysis is performed to determine the probability of an attacker being able to brute force the algorithm and how the moving target mechanism mitigates it. A data transfer equation is developed to calculate how long in seconds the algorithm would take to transfer q bits of information with a transfer rate of p packets per second while evaluating n bits of data per packet. Finally, a mitigation and detection analysis is performed on the algorithm.

Future Work

The most important part of the future work is to establish a more covert marking technique for the general algorithm and to improve the proof of concept. The general algorithm is robust enough to provide security against brute forcing because of the rotating permutations but if the marking mechanism is found by a third party who is monitoring the traffic, then the covert channel is discovered. Although the third party cannot read the data, they can shut down the channel which prevents covert communication. Another important part of the future work is to perform a through and in-depth steganalysis by performing experiments on how an active or passive warden would behave in a scenario where this network steganography technique is applied.

The proof of concept ignored the fact that most of the time, the users will not be in the same localized private network. Part of the future work should focus on augmenting the capabilities of the proof of concept. The proof of concept should be upgraded to have the ability to allow for communication between hosts outside of local networks. Additionally, the permutation and simulated ack features for mitigating dropped or altered data packets were not implemented. Adding those features would enhance the security of the proof of concept. Finally, allowing the proof of concept to use a packet that was not generated by the program, i.e. one that is already present between the two hosts, would increase the covertness of the program.

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