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**DEVELOPMENT OF INFORMATION ASSURANCE PROTOCOL FOR LOW BANDWIDTH NANOSATELLITE COMMUNICATIONS**

by

Cervando A. Banuelos II

**September 2017**

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**DEVELOPMENT OF INFORMATION ASSURANCE PROTOCOL FOR LOW BANDWIDTH NANOSATELLITE COMMUNICATIONS**

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ABSTRACT

Nanosatellites provide a light, efficient, and cost effective way for research institutions to carry out experiments in low Earth orbit. These satellites frequently use the ultra-high and very high frequency bands to transfer their data to the ground stations, and oftentimes will use the internet protocol and the Transmission Control Protocol as a standard for communication to ensure the arrival and integrity of the data transmitted. Due to bandwidth limitations and signal noise, these connection-based protocols end up accruing a large data bandwidth cost in headers and retransmission costs. Furthermore, due to connection unreliability, encryption and integrity checks present a challenge.

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LIST OF ACRONYMS AND ABBREVIATIONS

COTS commercial off-the-shelf

IP Internet Protocol

TCP Transmission Control Protocol

UHF ultra-high frequency

VHF very-high frequency

UDP User Datagram Protocol

NERDP Nanosatellite Encrypted Reliable Datagram Protocol

LEO low Earth orbit

CSP CubeSat Space Protocol

OSI

ISO

BER bit error rate

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# INTRODUCTION

## rESEARCH DOMAIN

Nanosatellites are small low Earth orbit (LEO) devices used to undertake space-based research in a cost effective manner. Nanosatellites typically have a mass of 1-10 kilograms, have a short life time of a few weeks or months in orbit, and are often constructed using commercial off-the-shelf (COTS) components. COTS components are typically inexpensive, readily available, and can be easily repurposed for space missions. The use of these components helps keep the mission prices low and allows for a larger number of research institutions to carry out experiments and demonstrations in LEO.

Currently, nanosatellites and their COTS components rely heavily on pre-existing and well established communication protocols. These protocols are the same ones used in ground based internet communications and build on the Internet Protocol (IP) stack. Specifically, researchers will use two of the most common protocols: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). These protocols operate at a network level on all computers on the ground, and provide a framework for communication to automate the transmission and receipt of data.

TCP is a connection-based protocol, meaning that it relies heavily on a persistent connection even if the connection is noisy or prone to errors in the data. TCP provides key services that are fundamental to the transmission of data such as retransmission of lost or deformed packets, acknowledgement of data received, integrity checks, and the ability to assemble the packets of data in the correct order. To achieve this, each TCP packet will contain anywhere between 20 to 60 bytes of data as a header containing the relevant information needed by the receiver to carry out these functions.

UDP on the other hand is a lighter protocol that does not rely on a persistent connection. UDP is a unidirectional packet sent by a transmitter to a receiver without any information for retransmission, or correct packet ordering. If an object is fragmented into discrete packets and transmitted with UDP, unlike TCP, these packets may or may not arrive, and they may or may not arrive in the right order without any mechanism to verify their order, without a mechanism to acknowledge their successful arrival to the recipient, and no way for the recipient to request the retransmission of a specific packet. UDP does provide a checksum for integrity validation of the packet, but not much more data is transmitted in its 8-byte header.

These data packets are frequently transmitted by nanosatellites over ultra-high and very-high frequency (UHF and VHF) bands. These radio frequencies allow researchers and the operators of the nanosatellites to communicate with the devices in orbit at a low financial cost as transmitting and receiving equipment is COTS. By using these bands, nanosatellite operators can also reduce the power consumption and internal space footprint of the communications components within the nanosatellite.

Nanosatellites provide an accessible opportunity for more institutions to carry out space-based research. The devices have lower expenses than other space missions, small, and the components are readily available to anyone. Since the launch of the first nanosatellites in the early 2000’s, the benefits provided rely heavily on the low cost and profile of the devices. Furthermore, the ability to transmit and receive the data from the devices is beneficial to research institutions who would otherwise have no way to extend their research projects to space exploration. To this end, it is important that a standard in data communication and transmission for nanosatellites be established to broaden the scope of the research capabilities of the nanosatellites. Said standard should take into account the technical limitations of the nanosatellites, be flexible in its application due to the various nanosatellite designs, be a software based solution, and provide an efficient mechanism for communication that improves upon existing communications protocols.

## Research problem and Motivation

The popularity of nanosatellites is due to largely to their relative simplicity and affordability. Unfortunately, these benefits come at a cost. These costs translate to signal noise, low-bandwidth, high packet drop rates, and low overall mission data transfers. These costs exacerbate the situation by limiting the range and length of experiments accessible and available, and by limiting the usage of well-established IP communication schemes and encryption methods

To make nanosatellites more accessible to multiple research institutions, and to simplify the communication schemes, researchers have designed nanosatellites to communicate over amateur radio bands in UHF and VHF using a variety of radio protocols. As mentioned above, the use of these protocols and these bands means that there is a relatively low data transmission rate accessible for space to ground communications. Surveys done by two teams, Bryan Klofas et al. in 2008, and Paul Muri and Janis McNair in 2012, show that nanosatellites, specifically CubeSats operating in the UHF band, typically have a baud rate ranging from 1200-9600 [1], [2]. Regardless of whether these satellites use transceivers either custom-built for the specific mission by the research institute, or use prefabricated COTS transceivers, if operating on the UHF or VHF band, a common communication protocol employed is the AX.25 protocol.

Klofas’ survey, dated in 2008, shows a comparison summary of the various communication transceivers, frequencies, in addition to the baud rate of 18 different satellites operating in UHF and VHF bands. This survey also specifies the data link layer protocol, Open Systems Interconnection (OSI) Layer 2 as defined by the International Organization for Standardization (ISO), used by these satellites. More specifically, the survey shows that out of the 18 satellites included in the paper, 14 devices utilize the AX.25 protocol for amateur packet radio [1]. Muri and McNair’s survey, shows a database of 30 satellites launched in the 2009-2011 timeframe; of these devices 16 utilized the AX.25 protocol [2].

The AX.25 packet radio protocol ensures the delivery of packet data encapsulated in frames and managed by the transceiver. This protocol provides a standard for the intercommunication between various ground stations and satellites in either half or full-duplex schemes. Unfortunately, this protocol does not intrinsically provide any support for the implementation of the IP protocols such as TCP or UDP, as those operate on the OSI Layer 3, the Network Layer [3]. The lack of network packet management functionality provided by TCP or UDP in the AX.25 protocol means that these protocols typically have to be added on top of the existing OSI Layer 2 much like those same IP protocols have to be used in addition to the Ethernet frames in standard internet communications.

From a security perspective, nanosatellite communication schemes lack a cryptographic method that ensures the confidentiality of the data transmitted. While there are some solutions that provide encryption of data, such as CubeSec and GndSec solutions devised by Challa et al. in [4], these solutions are hardware based. Limiting communications to specific hardware configurations places a constraint in the design and flexibility of nanosatellites. While hardware implementation of encryption may be faster for certain encryption methods as stated in [4], a low impact software encryption mechanism would be more favorable as it can be independent of specific hardware constraints. Additionally, using encryption methods such as AES means that if a large file is encrypted and transmitted, the receiver would have to wait to receive the whole object before decryption can begin which may not be in the best interests of the mission.

As mentioned above, TCP and UDP have their drawbacks in design and applicability. TCP is heavily connection based protocol that requires a persistent, connection, ideally running in full duplex mode. This allows the transmitter to receive acknowledgements while it transmits data packets. Unfortunately, due to the limitations of the AX.25 protocol in the amount of possible data transmitted per frame, the relatively higher noise rate of the UHF and VHF bands, and the size of the TCP header, TCP become unwieldly for nanosatellites with lower baud. At 9600 baud, a nanosatellite can transmit 9600 bits per second, and at half duplex this could present a large data cost to an already limited bandwidth.

An OSI Layer 4, Transport Layer, solution has been proposed by members of Aalborg University in Denmark called the CubeSat Space Protocol (CSP) [5]. This protocol was developed in C and modeled after the IP TCP standard and includes a header that is only 4 bytes long and supports eXtended Tiny Encryption Algorithm (XTEA) encryption and is designed to successfully integrate with several physical layer technologies. While this protocol does provide some additional functionality at a lower cost, it is limited to the specific physical layer drivers and is more centered towards network operations. This is reflected by looking at the packet structure and noticing that it uses 22 bits out of the available 32 just to establish a source, destination, and their corresponding ports [5]. Since most of the source and destination addressing can be done at the OSI Layer 2 for most radios, it is inefficient to use that much of the packet header in a redundant manner. Furthermore, CSP reserves several ports for buffer status, pings, and other network functions that may not be a priority for researchers or can again be derived from the radio protocol used. The use of XTEA does not allow partial decryption, as described above, and limits data validation to only after the entirety of the object has been downloaded. CSP documentation found in [5] does not readily outline the mechanism for packet receipt acknowledgement, packet retransmission, or data integrity checksums.

## Research Questions

The following questions are key for this investigation:

##### What are the processing, data overhead, and encryption costs of current communication protocols?

##### What are the processing and storage costs associated with using a one-time pad for encryption in nanosatellite communications, and how do they compare to CSP and XTEA?

##### Does the NERDP reduce the amount of data overhead and result in faster transfer times and/or a reduced number of packet exchanges than TCP?

## scope

The scope of this thesis is to investigate the technical needs of the small satellite and nanosatellite community operating in the UHF and VHF bands, focusing on their bandwidth their limitations and developing a versatile lightweight software solution that can meet those needs and increase the productivity of the satellite, labeled as the Nanosatellite Encrypted Reliable Datagram Protocol (NERDP). Focus will also include investigating the addition of confidentiality to the data payloads using a pre-loaded one-time pad (OTP) increasing the cybersecurity strength of the communications scheme. Development will target a software solution that can be run on COTS components, measure the performance of the OTP encryption, add integrity checks for the data transmitted, and add reliability to the data transmissions while maintaining hardware limitations in mind.

## Approach

The process used for this investigation determined the current limitations in the transfer of data from nanosatellites deployed by the Naval Postgraduate School Space Systems Academic Group, and a survey of protocols used and the challenges encountered. This focused primarily on the application of TCP and UDP as the main protocols for data transfer, as none of these satellites support encryption. The NERDP prototype developed then focused on demonstrating TCP-like functionality in data packet reliability and retransmission at a lower cost in data and performance in UHF and VHF. This prototype was developed to operate as a proof of concept in a virtual network with limited applications, but with a modular approach that and support the addition of increased functionality depending on mission requirements. NERDP was designed to operate strictly in OSI Layer 3 and higher, leaving the Data Link Layer to the hardware specifications. For the information assurance component of the prototype, and independent module using OTP encryption was developed and its performance was measured. This was done independently of the overall protocol as the protocol can support it and other types of encryption, but does not necessarily require it. The conclusions and performance assessments can be found in Chapters VI and VII.

## Thesis Structure

The remainder of this thesis is structured as follows:

Chapter II continues the discussion of bandwidth in UHF and VHF bands further outlining the problem space, includes a brief survey of current communication schemes and notable nanosatellites and CubeSats relevant to this thesis, discusses the need for cybersecurity in nanosatellites and outlines the status quo, and discusses the different methods of encryption with a particular focus on OTP.

Chapter III discusses the methodology for development, goals, and robustness of the OTP encryption algorithm designed for this thesis.

Chapter IV discusses the methodology of the development of the NERDP, the structure, reliability mechanisms, and the data overhead reduction of the Network Layer software based protocol proposed in this thesis, NERDP, and includes a comparison to other IP protocols.

Chapter V discusses the data analysis of the error propagation simulated in the encryption algorithm, and the data collected in the FM band testing.

Chapter VI summarizes the results of the encryption scheme and NERDP as functions of overall system performance. This will evaluate the systems costs and their feasibility along with any potential cybersecurity vulnerabilities.

Chapter VII will provide main conclusions arrived on the applicability of the prototype and encryption scheme proposed, and outline the future work and next steps.

# Background

This chapter discusses bandwidth limitations in the UHF and VHF bands by exploring typical nanosatellite communication schemes. The root of the issues is discussed, and notable nanosatellites and CubeSats are explored. These surveys provide further context of the problem space and the limitations currently encountered by nanosatellite developers. The text also provides a brief overview of cybersecurity and information assurance in nanosatellites, and a discussion on encryption with a focus on one-time pads.

## Problem Space: Low Bandidth in UHF and VHF bands

As described in [1] and [2], most nanosatellites communicate in the UHF range and have a baud rate typically of 1200 to 9600. Several factors limiting this baud rate include, but are not limited to the hardware used, the power available to the communications array, antenna type, time window for communication, and angle on the horizon. Variations in all of these factors can create not only fluctuations in the baud rate but also in the quality of the signal. Lower signal quality introduces random noise and errors, typically in the form of flipped bits in the payload, and can compromise the integrity of the overall object being transmitted. This loss of packets due to signal noise, measured as bit error rate, is part of the reason some nanosatellites use protocols like TCP or CSP as they allow for the retransmission of lost packets and packets deemed too compromised.

### Common Nanosatellite Frequency and Bit Rate Ranges

The UHF an VHF bands are defined by radar-frequency letter band nomenclature, and also by the International Telecommunications Union (ITU). These nomenclatures, while similar, can lead to some confusion. Radar nomenclature identifies the VHF band as a frequency range of 30-300 MHz, the UHF band as 200-1000MHz, the L-band as 1 - 2 GHz, and the S band as 2 - 4 GHz. Meanwhile The ITU nomenclature, while maintaining the same definition of the VHF band range, groups any frequency between 300 Mhz - 3 GHz as UHF [6]. Revisiting the surveys by Klofas et al., and Muri and McNair, shows that most CubeSats and nanosatellites transmit at the 435 MHz frequency [1], [2]. In the Klofas survey, of the 18 satellites examined, all but 3 devices operated on the range between 400.375 – 437.880 MHz with the outliers operating at 902 – 928 MHz and 2.4 GHz [1]. Muri and McNair, also showed similar results, with only 10 out of the 30 satellites recorded not operating in the ~437 MHz. frequency [2]. Researching this distribution further reveals that in an update to the Klofas’ survey to include CubeSats launched between 2003 - 2014, 112 out of 172 total transmitters recorded operated in the 437 MHz amateur radio frequency range, with an additional 40 devices still operating below 1000 MHz [7].

Bit rate is measured in amount of bits transmitted per second (bps) or baud rate, and is used to determine the rate at which data can be transmitted. On ground based systems, such as the internet, speed is typically measured in the megabit range (millions of bits per second) but due to the low power and the limited hardware of the nanosatellites, these ranges typically fall into the (kilobits per second) range. Again, the Klofas, and Muri and McNair surveys expose the data rates of several satellites. More specifically, out of 144 transmitters recorded by Klofas, including the other surveys, 121 transmitters operated at 9600 baud or less, with the second most common rate being 1200 bps [1], [2], [7]. These low bit rates are why these devices are labeled as low-bandwidth for the sake of this problem space and part of the reason why reducing data overhead is so important and significant.

Due to the prevalence of the 437 MHz frequency and a typical baud rate of 9600 or less in both early and more current nanosatellites, research and development of communication protocols should strive to operate at those target specifications. These specifications seem to provide the most cost effective hardware and communication packages for nanosatellites, as reflected by their popularity, but simultaneously also limit the usefulness of these devices. If experiments collect too much data, then it may be unfeasible for the data to be transmitted to the ground recipient. The problem is only exacerbated when a large portion of this limited bandwidth is needed to retransmit a large number of packets due to poor connection, and each of these packets has an unnecessarily large header attached to it.

### Bit Error Rate and Packet Loss

Data rates in satellites are dictated by the available power to the communications system, signal quality, distance between receiver and transmitter, atmospheric conditions, and many other factors. These factors impact the already limited bandwidth of the COTS components in nanosatellites and introduce errors in the bits transmitted. These errors can be resolved through error correcting schemes, and through data retransmission. These unavoidable occasional retransmissions is why protocols like TCP are preferred over protocols like UDP.

Error rates in data transmissions are known as bit error rate (BER), and are defined as the ratio of incorrect bits received divided by the total number of bits transmitted. This ratio is useful in evaluating the performance of the communication systems and to estimate the need for retransmission and error correction. In a 2012 report, authors Selva and Krejci utilize an estimated BER for calculations of approximately 10-5 [8]. While this estimate is only valid for a specific modulation used by the authors, it does give insight into the minimum BER expected for satisfactory performance by the communication devices.

BER impacts the integrity of specific bits that are transmitted, these bits then compromise entire bytes, and these result in compromised packets. Due to the low power of the transmissions, it is also possible for packets to not reach the ground station at all. These total packet losses result in missing data and, in the case of TCP, result in the ground station requesting multiple retransmission of packets. This constant change of state of the radio from receiving to transmitting accrues a time loss if the signal quality is poor enough to require multiple retransmissions. Furthermore, nanosatellites have a limited window of approximately 45 minutes of contact with the ground station per day. If changing states of the radio takes 1 second to transition between states, then the two seconds it takes to request a retransmission is 0.074% of the total time available per day. If an object requires multiple retransmissions to ensure integrity, then this accrued time from state switching is detrimental to the performance of the communication system. As described above, BER is unavoidable and by consequence so are retransmissions. Therefore, to ensure optimal data transfers, a protocol that improves on the TCP model and reduces the number of state changes would provide a better solution.

## Current nanosatellite communication standards

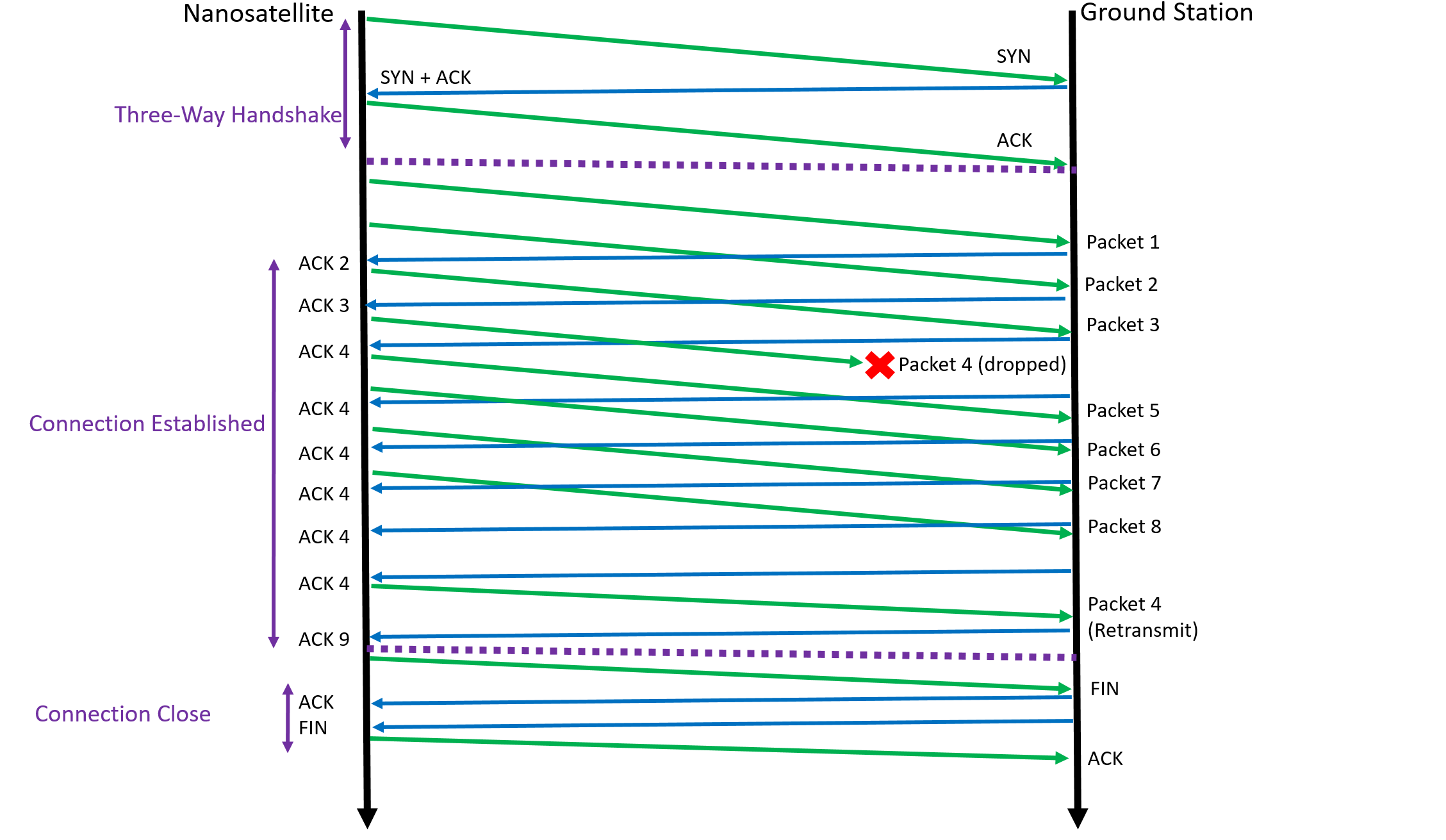
Current nanosatellites typically use the AX.25 packet radio protocol, as discussed above, and will sometimes encapsulate a Layer 4 protocol such as CSP, TCP, or UDP. Each of these Layer 4 protocols has advantages, disadvantages, and applicability, but all have a data overheads required in transmission. This overhead reduces the amount of data that can be transmitted by the satellite, and adds functionality not always needed in from the nanosatellite. Additionally, some of these Layer 4 protocols cause connectivity problems if the connection is unstable or reliable and compound the problem of reliability and retransmission, further increasing the accrued data overhead.

### Data Overhead

Due to the various designs and OSI Layer 2 implementations, such as AX.25, the calculations for optimizing data overhead focus on Layers 3 and 4. These layers, the networking and transport layers, provide the infrastructure for transferring data packets, and for dictating their behavior. In typical internet applications, Layer 3 is responsible for routing and packet forwarding structures like IPv4, while Layer 4 provides the architecture for the connection behavior in protocols such as TCP and UDP. Anything higher than Layer 4, for all intents and purposes in nanosatellites, can be considered payload data, though it should be noted that the header of Layers 3-4 is often included as part of the payload along with Layers 5+ when viewed in reference to the Layer 2 protocol.

Since nanosatellites use AX.25 for the delivery of packets, and are largely point-to-point communication schemes, a networking layer that includes routing information can be foregone as this layer can be used to route packets to various IP addresses in the same network, and even make the transition through different routers. Point-to-point communication through packet radio carried out through AX.25 does not require routing or communication with multiple nodes, therefore the implementation of a header, such as an IPv4 is not necessary and abandoning it can reduce the overhead by 20–60 bytes [9].

Abandoning the need for a Layer 3 protocol introduces some challenges for IP based transport layer protocols. TCP is reliant on a persistent IPv4 based connection, and its data header includes information on the source and destination IP addresses and ports. This information supporting the range of functionality of TCP results in a header of 20-60 bytes [10]. Using the above information, a transport layer protocol that is independent of the network layer can reduce the data overhead of each packet transmitted by 40-120 bytes. In relation to packet loss and retransmission, the costs of IP/TCP overhead accrue quickly. A time diagram of TCP transmission with packet loss, either from integrity failure or packet drop, (Figure 1) demonstrates the overly verbose nature of TCP that leads to a large amount of packet transmissions.



1. TCP time diagram for transmission of 8 packets with retransmission of packet 4.

Each packet transmitted under TCP will have an IP header and a TCP header. Assuming no options, the total headers for Layers 3-4 in this scheme is 40 bytes, or 320 bits, per packet. In 8 packets this data accounts for 2560 bits. At 9600 bits per second the data overhead accounts for 26.7% of the data transmitted per second, assuming the baud rate is negligibly affected by the Layer 2 AX.25 protocol.

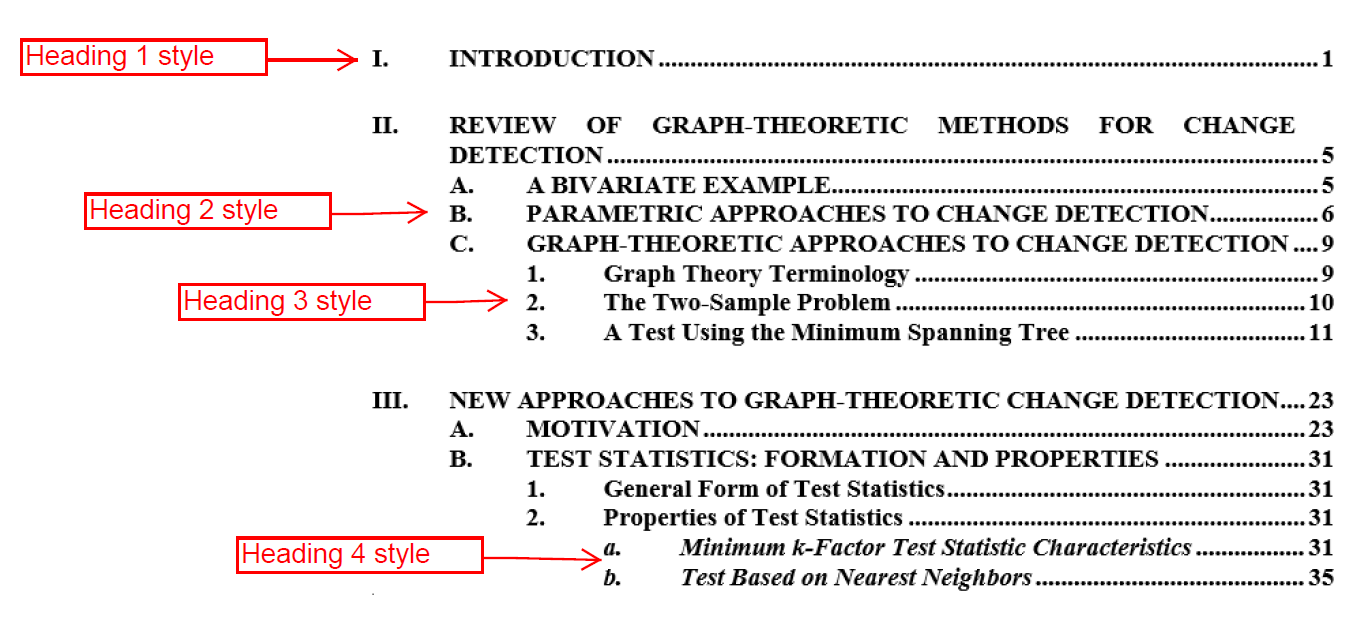
UDP, the other popular IP protocol in nanosatellites, is a connectionless protocol that still relies on the IP infrastructure of Layer 3. This Layer 4 protocol uses one-way datagrams to transmit data between two nodes. These datagrams provide a header per packet that includes source and destination ports, much like TCP, and also provides and integrity check for the data transmitted. The drawbacks of this protocol include the lack of functionality for retransmission and correct packet assembly order. TCP utilizes sequence numbers in the headers to assemble the packets in the correct order and detect if a packet is dropped. UDP’s lack of sequence check creates a challenge for data retransmission and object reconstruction. TCP also provides functionality to ensure the delivery of the packets through the form of acknowledgements per packet, while UDP has no such mechanisms. The advantage of UDP is its simplicity and significantly smaller header than TCP. Assuming 20 bytes are still used for the IP header, UDP only requires an additional 8 bytes as a header as opposed to the 20 required by TCP [11].

It should also be noted that the standards for both UDP and TCP outline 2 bytes for each of the destination and source ports in the protocol. These two bytes, or 16 bits, are unsigned integers and result in 216, or 65536, possible ports for data receipt and transmission [10], [11]. Such a large number of ports is useful in internet and network communications, but may be excessive for use in nanosatellites. A protocol with a reduced number of ports would reduce the overhead in headers at little to no cost in functionality.

To each heading topic, apply the heading style (**Heading 1**, **2**, **3**, **4**,or **5**) that corresponds to its level in your outline (see Figure 1). When you apply each heading style, the proper letter or number will automatically appear, and formatting will be applied. Figure 1 shows how the heading styles display your thesis outline in the Table of Contents, once they are applied to thesis text. Use headings only to introduce a new section of thesis text. Place paragraph text under each heading before introducing the next level of heading. There must be at least two headings for each heading level (A and B, 1 and 2, *a* and *b*, at minimum), or do not use the heading.

Note that **Heading 3s** and **Heading 4s** must be typed in uppercase and lowercase letters. Do not use **Heading 3s** to make a numbered list; use the **List Number** style or **List Bullet** style to accomplish that task.

**Heading 5** typically is used for subsections below the **Heading 4** level (see Chapter II, pp. 12–13). **Heading 5** also may be used under any heading level to number a series of single paragraphs (see Chapter II, p. 15–16).



When heading styles 1 through 3 are applied to text, they will appear in the Table of Contents.

1. Heading Levels and Their Associated Styles. Adapted from  
   Hawks (2015).

## BODY TEXT STYLES

To all paragraphs in the document, apply **ALL PARAGRAPH** style. There are styles for other elements (e.g., **FIGURE TITLE**, **List Bullet**, **List Number, Quote**) used within the body text.

### Figures

Formatting for figures in NPS theses may be different from what you are used to; therefore, please read and follow these instructions carefully. Figures 1 through 4 of this template show examples of the preferred format in various combinations of the possible elements. Figures 5 and 6 show accepted format variations.

* Figures should be styled as **IMAGE**. This centers the image and applies even white space.
* Do *not* include a title within your image, since it will be written in the figure’s caption, **hereafter called a “Figure Title.”** If a *borrowed* figure contains a title inside it, your Figure Title must be different.
* All figures should be readable if the words in them are meant to be read. You may need to re-create images when the source text is too fuzzy to read. Or, you may need to enlarge the image and place it on a horizontal page. Do this by inserting a “Continuous Section Break” at the start *and* end of your horizontally aligned information and changing the page orientation to “landscape.” Section breaks are available in Word’s “Page Layout” tab.
* In the body text, each figure must be referred to by its number prior to displaying the figure. Refer, for example, to Figure 23, without including its title.
* Although your figures must be explained in your text before they appear, their meaning must also be clear enough to stand alone.
* In your text, *do not* use descriptive words such as “above” or “below” when referring to figures.



**IMAGE** style—centers the image, puts correct spacing above and below

**FIGURE TITLE** style. If you choose to use sentence case (not shown), do so for *all* Figure Titles.

1. A Basic Figure

#### Figure Titles

Each figure must have a title. Type the title *outside* of the actual figure. Follow these NPS thesis style guidelines for Figure Titles, which, in some disciplines, are referred to as captions:

* Type your Figure Title *below* the figure itself, as shown in Figure 2.
* Use a short, definitive title that tells your reader the main topic and the main takeaway from your image.
* Try to limit your title to fewer than 12 words, since these will appear in your List of Figures.
* Use sentence fragments, *not* complete sentences.
* Use either title case or sentence case—*just be consistent with all your Figure Titles*. If you use title case, capitalize all words *except* prepositions, articles, and conjunctions. If you use sentence case, capitalize the first word, any proper nouns, and any word after a colon.
* Do not end a Figure Title with a period, *unless* the title is followed by a citation; adding citations to Figure Titles is covered next in Section b.

Once you have your title typed in, apply **FIGURE TITLE** style to the title. Word automatically inserts the word “Figure,” a sequential number, and a tab space for you, as shown previously in Figure 2.

#### Figure Citations

A citation is *required* if you did not wholly create the image or information yourself; placement of the citation is shown in Figure 3. A citation is not needed when all elements of the figure are your own creation.

For any figure that is not your original work, you must cite the source as part of the **FIGURE TITLE**, using the short-form citation for your chosen citation style.

* Place a period and space after the Figure Title but before the citation.
* If the figure is directly reproduced from a reference, use “Source: \_\_\_.”
* If you changed the original figure, use “Adapted from \_\_\_.”
* Chicago Notes and Bibliography users may use a footnote after the Figure Title instead of “Source:” of “Adapted from”: Figure 3. Caption Here12
* When the source is a webpage, include the name of the website owner; the URL alone is not sufficient.



Place citation, if applicable, after the title, as a new sentence.

Start citation with either “Source:” (exact image borrowed) **or** “Adapted from” (original was altered).

Citations should follow the same format as the reference style you use in your thesis text.

1. A Figure with a Title and a Citation in APA Style. Source:  
   Doe (2017).

NOTE: If you need to provide a full citation, or your sources are numerous, place it in a Secondary Caption (covered next in Section c), not with the Figure Title.

NPS theses and dissertations must comply with U.S. copyright law when using figures, illustrations, and images created by others. Those found in U.S. federal government documents are rarely copyrighted, but this should not be assumed.

You have several options when incorporating another person’s copyrighted work into your document: 1) obtain permission from the copyright owner, 2) follow item-specific licensing rights and restrictions, or 3) determine fair use, an exemption provided in U.S. copyright law for education and research. A determination of fair use must be made on an image-by-image basis, using a [four-factor fair use test](https://www.lib.umn.edu/copyright/fairthoughts).  For more fair use guidance, visit the [Dudley Knox Library’s Fair Use page](http://libguides.nps.edu/copyright/fairuse). For more information on copyright at NPS, visit the [Dudley Knox Library’s Copyright page](http://libguides.nps.edu/copyright/home).

#### Figure Secondary Captions, Separate from Figure Title (Optional)

Depending upon your discipline’s norms, you may need more than a summary Figure Title, whether to include justification for using the source, explain why certain data were presented and other data omitted, or provide more information about methodology used, for example. This additional information must be placed in a “secondary caption.” Refer to Figure 4 for an example of the format.



Secondary Caption. Optional extra information goes directly below the figure. Apply **Figure Secondary Caption** style.

If you would like to provide more information than what is in the Figure Title, provide it here, in a Secondary Caption. Apply **Figure Secondary Caption** style to Secondary Captions.

1. Placement of Optional Secondary Captions in Figure Title

You may add a Secondary Caption *between* the figure and the Figure Title:

* Write Secondary Captions in *complete* sentences, not fragments, unless you are listing legend elements.
* Use sentence case (capitalize first word and proper nouns only).
* Apply **Figure Secondary Caption** style to this secondary text by highlighting it and selecting the style from your Styles palette.

#### Optional Figure Format: Multi-Line Figure Titles, Combining Figure Title and Secondary Caption

Depending upon your discipline’s norms, Figure Titles may be composed of more than one sentence, to include justification for using the source, explanation on why certain data was presented and other data omitted, or more information about methodology used. See Figure 5 for an example of a multi-line Figure Title.

Create multi-line Figure Titles as follows:

* Use a sentence fragment, not a complete sentence, for the first sentence, which summarizes the primary point of the image.
* If you are adding source information, place a period and space after the first sentence and then type the citation in its own sentence.
* Write all other (secondary) sentences in *complete* sentences, not fragments, unless you are listing legend elements.
* Use sentence case for all other sentences after the first and the citation.
* Insert a “style separator” *before* secondary caption text. [Get the instructions here](https://my.nps.edu/documents/105790666/106471207/Multiline_Figure_Title_Instructions.pdf). These secondary captions will remain in your text as a continuation of the Figure Title but will *not* appear in your List of Figures.

**Optional format:** Multi-line Figure Titles are also accepted, provided only the first line is visible in the List of Figures

*See Section d for format instructions*



1. Variation—Multi-Line Figure Title, with First Sentence Only in List of Figures. Adapted from Doe (2017).

You will need to insert a style separator after the Figure Title and before secondary text; instructions are provided in Section d. Use sentence case in secondary text.

#### Optional Figure Format: Figure Title above Figure

You may elect to place all of your Figure Titles ***above*** your figures. In this case, place the more detailed Secondary Caption *below* the figure:

* Write Secondary Captions in *complete* sentences, not fragments, unless you are listing legend elements.
* Use sentence case.
* Apply the **Figure Secondary Caption** style to this secondary text by clicking into it and selecting the style from your Styles list.
* Your thesis processor will adjust your **IMAGE**, **Figure Title, and Figure Secondary Caption** styles to accommodate this optional format. Please do not attempt to do this yourself.
* Refer to Figure 6 for an example of this format.

1. Variation—Figure Title above Figure



***Optional format***:   
If you choose to place Figure Titles ***above*** your figure, do so for ***all*** figures

If you placed all of your Figure Titles above your figures, then place the Secondary Caption **below** the figure, as shown here. Your thesis processor will adjust your **IMAGE**, **Figure Title**, and **Figure Secondary Caption** styles during your Initial Review to accommodate this format.

### Tables

Follow the NPS thesis style guidelines for Figure Titles, with these exceptions:

* Table Titles are to be placed *above* the tables themselves, never below.
* Apply **TABLE TITLE** style to each short, descriptive Table Title. The template will insert “Table” followed by the sequential number, a period, and a tab space before your descriptive title.
* Notes or legends should be placed *underneath* the table and must be aligned with the left side of the table and placed *underneath* the table. Apply **TABLE NOTES** style to these additional descriptive details. After applying the **TABLE NOTES** style, on the “View” tab, check the “Ruler” box to see the ruler. Click on the square underneath the triangles to the left and drag the notes in place.
* Use **Normal** style on the tables themselves, do not use IMAGE style.
* Place citation, if any, after the Table Title, as its own sentence. See   
  Table 1 for an example of where to place the citation.
* If the table is directly reproduced from a reference, use “Source: \_\_\_.”
* If you have made changes to the original table, use “Adapted from \_\_\_.”
* If you need to use the full citation, or if your sources are numerous, place the citation in Table Notes.

**Tables must be no wider than paragraphs.** Landscape the page if needed.

1. Styles to Use and Element Placement for Figures and Tables.  
   Source: [5].

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Style to Use on Picture** | **Style to Use on Title** | **Placement of Title** | **Style to Use**  **for Extra Information** | **Placement**  **of Extra Information** |
| **FIGURE**  **Preferred Format**a | IMAGE | FIGURE TITLE | Below figure | Figure Secondary Caption | Between figure and Figure Title |
| **FIGURE**  **Optional Format** | IMAGE | FIGURE TITLE | Below figure | None—Figure Title  is composed of multiple sentencesb | N/A |
| **FIGURE**  **Optional Format** | IMAGE | FIGURE TITLE | Above figure | Figure Secondary Caption | Below figure |
| **TABLE** | Normal | TABLE TITLE | Above table | TABLE NOTE | Below table |

You many include notes or a legend underneath a table. Align them with the left side of the table.

aPick one of the figure formats offered in this table and use it consistently throughout your thesis.

bSee Section d for instructions on how to do multi-line Figure Titles.

Add another paragraph return under each table to separate the table from the text

Apply **TABLE NOTE** style to notes

Align Table Notes with left side of table. (In the View tab, select Ruler to show ruler. Click on the square under the left triangles and drag in place).

### Bulleted and Numbered Lists

Guidance for bulleted or numbered lists is as follows:

* Apply **List Bullet** style to bulleted lists and **List Number** style to numbered lists.
* To restart a numbered list at “1,” right click on the first item and choose “Restart at 1.”
* Avoid using a mixture of bullets, numbers, or dashes, for different lists in your thesis.
* Generally, bulleted and numbered lists are punctuated with periods only if the bullets consist of complete sentences.

### Block Quotes

Quotations of five or more lines are to be styled as **Quote** style, with no quotation marks around the quote. This signals that the material is quoted. For formatting purposes only, the quotation becomes a separate paragraph. Citations go outside the period (block quotes only).

Remove quotation marks from around block quotes

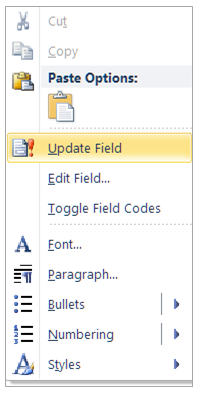
Quotations are understood to be excerpts; therefore, ellipses are usually not used at the beginning of a quotation. Ellipses *are* used in the middle of a quotation where a portion of the text has been omitted. This is an example … of correct use of ellipses. Ellipses may also be used at the end of a quote that is grammatically incomplete. For quoted material within a block quote, use double quotation marks. Citations go outside the period for block quotes only, like this. (Naval Postgraduate School, 2017)

To continue the paragraph visually (if desired), remove the paragraph indent from text following a block quotation as shown here (on the View tab, select Ruler. Click on top triangle ruler guide and slide 0.5 inch to left margin).

## Table of contents

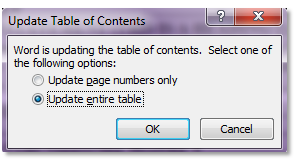
*Do not manually type your own Table of Contents.* After styling all headings in your thesis, right-click on the Table of Contents (text field turns gray).

##### Select Update Field



Crop excessive white space   
from images

##### Then Select Update Entire Table



##### Each heading will appear in proper outline form.

A glance at the completed Table of Contents should provide an overview of the thesis and act like an outline but not weigh down the reader with detailed information. Word will also update the Lists of Figures and List of Tables on command, as described for the Table of Contents.

## zotero, refworks and the like

If you use reference-list generating software, such as RefWorks, ensure that you fill in all fields completely and accurately when creating your citation list. *You must edit the reference list for punctuation and formatting* once the footnotes (if you use Chicago footnote style) and List of References are imported. To edit most lists, you must remove the field code. Do this by pressing Shift + Control + F9 at the same time. In Word’s citation manager, click on the list and choose “convert to static text.” If problems arise, see a Thesis Processor for help.

**RefWorks/Write-N-Cite users:** Before submitting for Final Review, click option to “Remove Field Codes,” after importing the List of References (you will find this option under the “Tools” menu in Write-N-Cite). *Save a copy of the thesis for your records before removing the field codes.* See a Thesis Processor or the library for help.[[1]](#footnote-1)

Also, RefWorks users must abandon the check-in/check-out feature of SharePoint. Instead, download the thesis from SharePoint, make edits, and then reupload the file to SharePoint (Write-N-Cite cannot access files in password-protected sites such as SharePoint).

The library offers citation management tools [here](http://libguides.nps.edu/citation/management).

## blank pages

Place each new chapter on an odd-numbered page (this should be done before submitting for Final Review). You may need to remove or insert intentional blank pages to achieve this. To add a blank page, place the cursor after the last word on the current page, then press Control + Enterto insert a new page in your file. On the style list, click **BLANK PAGE**. Type “THIS PAGE INTENTIONALLY LEFT BLANK.”

## Cross referencing

Referring to the wrong figure/table number is a top error found in final reviews!

You must mention each figure and table by label and number in your narrative. If you have many figures and tables, you might want Word to keep track of the figure and table numbers for you as you write and revise. Follow these steps to have Word insert cross references for you:

1. First, remove the period and tab from the **FIGURE TITLE** and **TABLE TITLE** styles (Style Palette🡪right click on style name🡪modify🡪format🡪numbering🡪define new number format).
2. To insert a cross reference, in the **References** tab, click **Cross-reference**. Choose **Numbered item** under “reference type,” and **Paragraph number** under “insert reference to.”
3. To update the cross references as you work, select all text (Control + A) and press F9. Follow prompts to update all linked content.
4. Next, when you are sure all figures and tables are in their permanent positions, highlight all **body** text starting from page 1 and press Shift + Control + F9. This breaks the field code from the cross references.
5. Finally, reinsert the period and tab in the **FIGURE TITLE** and **TABLE TITLE** styles.

## equations

To create equations, use MathType, which you can download from the NPS Technology [webpage](http://www.nps.edu/Technology/Downloads/SoftwareLibrary.html). DO NOT use the Insert, Equation option in Microsoft Word because math symbols could disappear when the file is converted to PDF. Do not clear coding from your thesis in one fell swoop by selecting all text and removing the code. Doing this will end up converting all of your equations to pictures.

The most popular format for equations is to center them and place the equation number on right margin (choose “Right-numbered” equation in MathType to achieve this). Whether you number your equations is at your discretion.

5x=10 (1)

If you created equations outside of MathType, or if you created equations in MathType without first numbering them but now want them numbered, follow these instructions:

1. Place your cursor in front of the equation, go to your style list, and choose either **Equation** or **MTDisplayEquation**.
2. Then, press tab. Your equation should jump to center of the page. If it does not, remove extraneous space and tab markings. There should be only one tab space.
3. Place your cursor *after* the equation and press tab. The cursor will jump to the right margin.
4. Now click **Insert Number** on the MathType menu if you want MathType to number your equations (to format the numbers, click **Insert Number**). Or, you can manually number your equations.

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# SAMPLE CHAPTER

Do no parrot headings (notice this is an immediate repeat of the chapter title) if you immediately begin a chapter with a subsection heading

**~~X. SAMPLE CHAPTER~~**

This is how a properly formatted chapter would look. Each section of a chapter should be substantial enough to warrant a heading. *There should be at least two sections per subheading level*. *Do not stack headings without text in between*. Heading 5 style may be used under any heading level if short, numbered paragraphs are desired.

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Use Heading 5 style to number a collection of paragraphs—do not use Headings 2 to 4

##### Heading 5 to Number Paragraphs (Optional Use)

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# appendix. Optional

Appendix titles are also styled as **Heading 1**, minus a roman numeral—backspace to remove the roman numeral. Then, type “Appendix,” two spaces, a letter, and a title: “APPENDIX A. DATA.” *However,* *if you have only one appendix, do not add the letter “A.”*

If you apply Heading 2 style in your appendices, and the lettering does not begin with “A,” simply right click on the first Heading 2 of the appendix, and choose “Restart at 1.”

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# List of References

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| --- | --- |
| [1] | B. Klofas, J. Anderson and K. Leveque, "A survey of CubeSat communication systems"," in *5th Annual CubeSat Developers' Workshop*, 2008. |
| [2] | P. Muri and J. McNair, "A survey of communication sub-systems for intersatellite linked systems and CubeSat missions," *Journal of Communications,* vol. 7, no. 4, pp. 290-308, 2012. |
| [3] | W. A. Beech, D. E. Nielsen and J. Taylor, "AX.25 link access protocol for amateur packet radio version 2.2," Tucson Amateru Packet Radio Corpoeration, 1997. |
| [4] | O. N. Challa, G. Bhat and J. McNair, "CubeSec and GndSec: a lightweight security solution for CubeSat communications," in *26th Annual AIAA/USU Conference on Small Satellites*, 2012. |
| [5] | "CubeSat Space Protocol: A small network-layer delivery protocol designed for CubeSats," Aalborg University, 2008. [Online]. Available: https://github.com/libcsp/libcsp. [Accessed 3 July 2017]. |
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| [7] | B. Kolfas, "CubeSat radios: from kilobits to megabits," in *Ground System Architectures Workshop*, Los Angeles, 2014. |
| [8] | D. Selva and D. Krejci, "A survey and assessment of the capabilities of CubeSats for Earth observation," *Acta Astronautica,* vol. 74, pp. 50-68, 2012. |
| [9] | Information Sciences Institute, University of Southern California, "Internet Protocol: DARPA Internet Program Protocol Specification," Defense Advanced Research Projects Agency, Arlington, Virginia, 1981. |

Apply **Reference List** style to your list of references to re-create or retain the formatting of this page. Remove manual line spaces that you have entered between entries, as the style comes with the proper spacing.

A *bibliography* is uncommon in NPS theses; a list of references is the standard. A bibliography differs from a reference list in that it also includes sources you consulted, but did not cite.

All in-text citations must have a matching entry in the list of references, with few exceptions; consult your citation style guide.

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/documents/105790666/106471216/Thesis\_Template\_Times.docx (**APA style**)

[1] B. Orend, *Morality of War*, 2nd ed. Tonawanda, NY: Broadview Press, 2013. (**IEEE style**)

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