COVERT COMMUNICATION NETWORKS

A Dissertation

by

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ABSTRACT

A covert communications network (CCN) is a connected, overlay peer-to-peer network used to support communications within a group in which the survival of the group depends on the confidentiality and anonymity of communications, on concealment of participation in the network to both other members of the group and external eavesdroppers, and finally on resilience against disconnection. In this dissertation, we describe the challenges and requirements for such a system. We consider the topologies of resilient covert communications networks that: (1) minimize the impact on the network in the event of a subverted node; and (2) maximize the connectivity of the survivor network with the removal of the subverted node and its closed neighborhood. We analyze the properties of resilient covert networks, propose measurements for determining the suitability of a topology for use in a covert communication network, and determine the properties of an optimal covert network topology. We analyze multiple topologies and identify two constructions that are capable of generating optimal topologies. We then extend these constructions to produce near-optimal topologies that can "grow" as new nodes join the network. We also address protocols for membership management and routing. Finally, we describe the architecture of a prototype system for instantiating a CCN.

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De oppresso liber.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION TO COVERT COMMUNICATION NETWORKS

The Internet is a great conduit for the promulgation of freedom of speech and protection from censorship. For many people, the Internet has provided a vehicle through which they can communicate, connect, organize and support one another. However, many who send emails, surf web sites, or chat with acquaintances do so assuming that their communications will never be observed by anyone other than their intended recipient. For most people, a sense of privacy is assured by simply using the Internet in a way that is legal and inconspicuous. Unfortunately, they are relying on the relative obscurity of their communication instead of the protection of any formal mechanisms. Often, people are relatively safe in their communication, not because they are unobservable, but because they are uninteresting to a potential adversary. Thus, the Internet provides only the illusion of privacy. We see this demonstrated again and again in cases when people lose jobs, relationships, or worse from the revelation of communication intended to remain private.

Various technologies have attempted to provide users with protection from the milieu of threats to their privacy. Through the use of codewords or message encryption, users are able to protect the content of their messages. Through steganography, covert channels and anonymity protocols, they are able to communicate in a more covert fashion; that is, the communication itself is hidden from an observer. Many of these approaches have been used in one form or another throughout history. With the advent of the Internet, these approaches have been adapted with significant success. In some cases, however, these approaches do not individually provide adequate protection.

1.1 The Need for Covert Communication

Consider the case in which members of some oppressed minority, suffering at the hands of an authoritative regime due to political, religious or cultural differences need to communicate with each other in the presence of a powerful adversary. We assume that the adversary can monitor and correlate traffic across large portions of the network or pressure ISPs to map IP addresses to real-word identities. Examples of such groups include so-called insurgencies and resistance movements [32] where a number of agents operate and communicate undetected by intelligence and law enforcement agencies. Similarly, news organizations may communicate with individuals despite network communication surveillance. Political groups may need to organize demonstrations in a way to prevent reaction by their opponents [40]. Finally, groups may need to communicate in situations where authorities seek to silence any activities that may be seen as subversive [64].

In this dissertation, we study the feasibility of communication tools to protect participants in such high-risk environments from being discovered. For this, we start with the premise that a peer-to-peer (P2P) overlay network architecture is a good starting point for this investigation.

1.2 The Criteria for a CCN

The criteria for this type of network are significantly more stringent than for traditional privacy and anonymity networks such as *Tor* [17]. Traditional means of Internet communications, such as email and instant messaging, would not be protected. Though encrypted traffic would provide *confidentiality*, the adversary could easily identify those communicating with known dissidents or persons of interest.

The group could use anonymous communications systems, which provide *message anonymity*. Using such systems, the adversary would be unable to tell (1) the contents of the message; (2) the origin of the message; or (3) the destination of the message. Such systems satisfy confidentiality requirements through cryptography and provide unlinkability between messages and participants [9, 10, 12, 17, 21]. This would provide some level of protection. However, anonymity networks do not attempt to obscure their presence; so if the authorities are able to affiliate the use of the anonymity system with activity deemed subversive, then simply participating in the network may be sufficient to place participants at risk.

It is important to distinguish anonymity from *pseudonymity*. Pseudonymity is the use of pseudonyms as identifiers [49]. Pseudonyms provide network identities that are unlinkable to real-world identities [9, 50]. Thus, pseudonyms provide persistent identities within a network that allow participants to communicate in such a way that is resistant to correlation with their real-world identities.

Membership concealment, orthogonal to both encryption and anonymity, ensures that any eavesdropper (either internal or external to the communication network) will have low probability of identifying participants [61]. When examining traffic across an anonymity network, if the adversary can correlate a network address such as an IP or email address to a real-world identity, then membership concealment is compromised.

Resilience is the ability of a network to maintain connectivity among participants in the presence of node failures. Though, important to any network, given the nature of a group relying on a CCN, the threat to the group posed by a powerful adversary, the membership-concealment topological limitations, and the difficulty of reestablishing network connectivity in the event of node failures/subversions, covert communication networks must be particularly resilient against disconnection.

As such, the communication network used by the group has four criteria. First, the communication has to be private; that is, the communication is protected against an adversary reading the contents of the message. Second, the communication has to be anonymous; that is, the adversary shall not identify who among the participants talks to whom. Third, the network participation must be concealed; that is, the adversary must also not be able to identify whether a particular individual is a participant in the network. Finally, the network must be resilient against disconnection; that is, it must remain connected even if the adversary is able to subvert a participating node.

To avoid confusion, we need to clarify the terms *covert* and *clandestine*. According to the United States Department of Defense Joint Pub 1-02, a covert operation is an operation that is so planned and executed as to conceal the identity of or permit plausible denial by the sponsor [32]. In contrast, clandestine operations place the emphasis on concealment of the operation rather than on concealment of the identity of the sponsor. We modify these definitions to fit our context such that clandestine conceals the object while covert conceals the identity of the participants. We distinguish *covert communication* from membership concealment in that covert communication is resilient against disconnection. Thus, we now define *covert communications networks.*

Definition 1.2.1. *A* **covert communications network (CCN)** *is a connected, overlay, peer-to-peer (P2P) network being used to support communications within a group in which the survival of the group depends on confidentiality and anonymity for communications, concealment of participation in the network to both other members of the group and external eavesdroppers, and resilience against disconnection.*

Such networks include traditional privacy preserving scenarios, clandestine networks, sensor networks deployed in adversarial environments, and many others.

1.3 Outlook

In this dissertation, we explore these requirements in further detail and address their application to Covert Communication Networks. The goal of this research is to provide the basis and design for an application that will protect both the identity of the members of at-risk groups and the communication of such a group while providing resilient networks that are resistant to disconnection.

In Section 2, we review the state of the field in areas related to covert communication networks. We briefly introduce steganography and covert channels. We describe several anonymous communication systems and a membership-concealing overlay network. We also briefly describe delay-tolerant networks.

In Section 3, we provide an operational overview of CCNs. This section provides a high-level view of a CCN and describes some of the design choices available. We also introduce the importance of topology in a CCN and describe our threat model.

Section 4 presents an approach to measuring CCN topologies in order to balance the membership concealment and resilience requirements. This measure, *subversion impedance*, provides a way to classify the appropriateness of a topology for use in a CCN. Results in this section were published in [44].

Section 5 measures the suitability of several common topologies for use within a CCN. This section extends the work in the previous section: first, by describing and applying subversion impedance in the average case to several common peer-to-peer topologies; then, by describing two topology construction algorithms with near-optimal subversion impedance that can contain an arbitrary number of nodes. Some of the results in this section were published in [45].

Section 6 measures the suitability of several common random topologies for use within a CCN. First, we extend our subversion impedance measures for application on random graphs. Then, we examine Erdös-Rényi random graphs and the Barabási-Albert construction for scale-free graphs, analyzing each for their suitability for use in CCNs.

Section 7 examines membership management. Membership management in CCNs is much more difficult in CCNs given the need for membership-concealment. Thus, steps must be taken to protect network addresses. This has significant impact on the join protocol and healing from node failures.

Section 8 examines routing within a CCN. Routing in CCNs is fairly straightforward. The constructions for deterministic topologies are such that nodes can locally calculate routing paths for traffic. In random topologies, we can easily apply common Internet routing approaches.

Section 9 describes the results of our prototype implementation, and concluding remarks are in Section 10.

2. PREVIOUS WORK IN AREAS RELATING TO COVERT COMMUNICATION NETWORKS

The objective of covert communications is to protect both the communication and the communicating parties. By its nature, covert communication is very close to information hiding techniques from steganography and covert channels as well as networks that protect their participants such as anonymity networks, and membership-concealing overlay networks. Covert communication rely on cryptography for confidentiality of the communication and extends membership-concealing overlay networks in such a way as to make them resilient to disconnection. In the following sections, we give an overview of cryptography, steganography and covert channels, describe the underlying technologies for anonymity networks and membership-concealing overlay networks, and compare the objectives and requirements of these networks to that of covert communication networks.

2.1 Cryptography

Cryptography provides confidentiality by rendering the communication unreadable to an eavesdropper. The most common methods used in computer networking can be classified as either *symmetric* or *asymmetric* cryptography. In symmetric cryptography, the sender and receiver share a common key used to *encrypt* and *decrypt* message traffic. In asymmetric cryptography, a sender uses a *public key* to encrypt message traffic. The receiver has a *private key* to decrypt message traffic. Thus, the public key can be publicly advertised and distributed, but any message encrypted with the public key can only be decrypted by the owner of the private key.

Symmetric encryption and decryption is usually faster to compute than asymmetric encryption and decryption. Thus, for near-real-time private communication, asymmetric cryptography is used to exchange symmetric keys which are then used for the remainder of the session.

2.2 Steganography

Steganography has been used in various forms for thousands of years [11, 48]. In steganography, messages are embedded in some other form of information, such as an image, text, video or audio in such a way as to conceal the message. Most steganographic techniques used today on the Internet exploit the structure of popular file formats. The message, known as the *plaintext*, is embedded in a *covertext* or *coverfile* producing a *stegotext* which is then sent to the recipient.

This may be accomplished by simply appending the plaintext after the EOF (end of file) tag in a JPEG coverfile [11]. The added data is ignored by computer applications and the image is unaffected. More sophisticated approaches embed data in the least significant bits of the coverfile [60, 65]. With these approaches, the embedded data is inconspicuous even when examining the raw file, and the coverfile is modified in a way that is only detectable if the modified file can be compared with the original.

Steganography provides communication between parties such that the existence of the communication is unknown to an eavesdropper. Steganographic messages are less likely to arouse suspicion than encrypted messages; thus, protecting both the message and the communicating parties.

2.3 Covert Channels

Covert channels are used for the secret transfer of information [69]. Similar to steganography, covert channels hide communication by embedding the message. However, instead of hiding a message in other content, covert channels usually either use something unintended as a communication channel or use a communication channel in an unintended way in order to hide and transmit a message, allowing messages to be transmitted in plain sight of possible observers such that they remain undetected; instead, relying on “security through obscurity”.

Use of covert channels in computer systems were first described by Lampson in 1973 as a means for a high security level process to leak information to another low security level process within a mainframe [35]. In computer networking, covert channels are often described as transmission channels used to transfer data in a manner that violates security policy [59]. As such, they exploit network protocols by using them in unintended ways as message carriers. For example, the message could be encoded in unused or reserved bits of frame or packet headers [29, 34, 69]. More complex mechanisms manipulate inter-packet timing in order to pass a covert message [7, 47].

Though the messages are concealed, steganography and covert channels do not necessarily hide the fact that communication is occurring. If the source and destination of the communication is identifiable, then the communication is only clandestine. As such, an adversary can treat any message traffic with a known subversive as suspicious regardless of the message contents. However, they hide the intended message while providing mechanisms to facilitate the creation of a “cover for action”; that is, the credible pretext for the communication to occur. As such, neither steganography nor covert channels provide membership concealment. Such techniques can, however, be combined with other approaches to ensure that the communication is, in fact, covert.

2.4 Anonymity Networks

While encryption, steganography, and covert channels all hide the content of a message, *anonymous communication* attempts to hide the sender and/or receiver of the message. More formally, the anonymity of a subject describes how identifiable the subject is among a set of other subjects. A number of metrics exist that attempt to measure anonymity, of which the simplest and most intuitive is the *anonymity set* [49]. The anonymity set of a subject s describes the set of other subjects among which s is not indistinguishable. Thus, anonymity enhancing technologies attempt to enlarge the anonymity set, and their effectiveness is measured in the resulting order of the anonymity set. More sophisticated measures attempt to capture the probability distribution of identification within the anonymity set [15, 24] or even capture systemic biases in the identification [70]. In anonymity communication systems, this is achieved by de-linking the real-world identity of network participants from the messages sent over the network.

For example, in traditional P2P overlay networks, where anonymity is not an issue, IP headers are sent unencrypted to facilitate end-to-end routing. As a result of this, the IP information is visible to an adversary that is in a position to observe the message traffic (perhaps observing at a firewall or router along the path). The adversary can use the information from the IP header to correlate the message to both a source and destination.

Anonymity networks have been studied and deployed for several years. An anonymous network may provide *sender anonymity* through unlinkability between the sender and the message or *receiver anonymity* through unlinkability between the receiver and the message, or both. Formally, *unlinkability* of two or more items of interest from an attacker's perspective means that within the system, the attacker cannot sufficiently distinguish whether these items of interest are related or not [49]. We say that an anonymity network provides unlinkability if an adversary cannot determine if two nodes are communicating. These networks are primarily built from the foundational ideas of David Chaum and are usually classified as either mix-style networks or DC-networks [9, 10].

Since the eavesdropper cannot infer the sender from the information in the packet, the anonymity set becomes the set of participants in the mix network. Each mix in the chain cannot know if it is receiving the message from the source or from another mix. Thus, sender anonymity is provided. Likewise, if the current mix does not know if it is forwarding the message to another mix or to the message's final recipient, then receiver anonymity is provided.

Undermining the anonymity provided by these systems usually involves attempting to correlate message traffic observed by the adversary in one portion of the network with traffic observed in a different portion of the network. Examples of such attacks exploit the timing behavior of communication protocols [70] or watermark the traffic [62]. Thus, mixes often use batching and timing modifications as additional anti-correlation measures.

2.4.1 Mix Networks

The earliest anonymous communication systems were *mix networks*. First described by Chaum [9], a mix is a process that accepts encrypted messages as input, decrypts each message in order to determine its destination, then batches messages with a common destination together, and forwards some or all of the messages in the batch. Mix networks provide anonymity by forwarding a message through a chain of mixes, each of which will strip out the source information and replace it with its own, and then forward the message to the next mix in the chain [25, 39]. Mixes are *high-latency* networks in that they intentionally delay the delivery of messages in order to protect against timing- and signature-based attacks. These delays could be on the order of hours or even days between the time the message is sent and then received.

A participant encrypts message M and a random bit string R_0 with the public key K_A of the recipient A. The result is embedded in an encrypted message to mix X using the mix's public key K_X as follows:

$$K_X(R_1, K_A(R_0, M), A).$$

where R_1 is also random bit string. The resulting ciphertext is then sent to Mix X, which can use its private key to retrieve $K_A(R_0, M)$ and the destination A. $K_A(R_0, M)$ is then forwarded to A. A can decrypt the received packet and retrieve the message M. R_1 and R_0 are simply discarded but are included in the encryption to help prevent an adversary from identifying two identical messages encrypted under the same asymmetric key.

Type I remailers, also known as cypherpunk remailers [13], consist of a set of mixes that are distributed across the network. A client picks a sequence of mixes to form a *route* through the network. The message is embedded in a nested set of encryptions and addresses for each *hop* along the route created by using the public keys of each mix. Each hop first uses its private key to decrypt the message it receives, then removes the address of the next mix, and finally forwards the payload to the next mix until the last mix in the route sends the message to the destination. Unlike Chaum's design, however, cypherpunk remailers do not add padding nor provide any explicit batching and delaying.

Cypherpunk remailers supported anonymous replies through a construction called *reply blocks* or through the use of a *nymserver*. A reply block is constructed in a layered manner by the sender similar to a normal message and passed to the recipient. The recipient then can attach any response to the reply block which is then routed through the network to the original sender according to the instructions provided by the reply block. Alternatively, a sender could send the constructed reply block to a nymserver. The nymserver stores the reply block and allocates a temporary pseudonym associated with the received reply block, storing the pair in a database. When the nymserver receives a message addressed to the pseudonym, it forwards the message through the remailer network using the stored reply block for that pseudonym.

The *Type II remailer*, also known as Mixmaster, adds message padding and batching [42]. Furthermore, Mixmaster tries to defeat replay attacks by recording the packet IDs included in the message header. If a mix receives a duplicate message, the duplicate is simply discarded. Mixmaster does not include support for anonymous replies.

The *Type III remailer* design, also known as Mixminion [14], protects against replay attacks by each mix keeping a hash of each recently processed message. All mixes periodically rotate their keys and discard their history. Messages encrypted with the old key are no longer accepted and cannot be replayed. Thus, Mixminion servers must only retain the history of previously processed messages for a shorter amount of time. Mixminion uses a distributed set of redundant directory servers to provide clients with information about the current mixes in the network and supports anonymous *single-use reply blocks* (SURBs) which are indistinguishable from normal forward messages.

2.4.2 Low-Latency Anonymity Networks

While high-latency anonymity networks work well for single messages, they are not appropriate for message streams or for TCP-like connections, where excessive delays in the delivery of acknowledgment messages trigger time-outs and retransmissions, and eventually cause connection resets. Low-latency anonymity networks are architected to carry latency sensitive communication (inclusive TCP connections).

Low-latency anonymity systems are often based on the notion of a proxy. While mixes explicitly batch and reorder incoming messages, proxies simply forward all incoming traffic (e.g., the packets of a TCP connection) immediately and typically without packet reordering.

Onion routing is a series of mixes where each message is encrypted in layers using the public key of each selected *onion router* with the message as the innermost layer [53]. The client selects a series of onion routers through which to establish a multiply encrypted tunnel, or *circuit*, through the network. Each onion router maintains a private and public key pair, the public component of which should be made known to clients. Asymmetric encryption is used to set up the circuit. The actual data is then encrypted using symmetric encryption in order to minimize the computational overhead. Each onion router strips off its own layer of encryption to reveal where to send the message next. If less than half of the onion routers are compromised by the adversary, untraceability can still be achieved. At a high level, onion routers operate similarly to a Type I remailer, however the underlying protocol provides low-latency communication.

Tarzan is a low-latency anonymity system loosely based on the original onion routing design[21]. It uses UDP as its transport protocol and a peer-to-peer "gossip" protocol to share information about other servers within the network. Thus, a network participant discovers other servers by asking a randomly selected neighbor for all the servers known to the neighbor. The participant can then repeatedly select newly learned random neighbors and repeat the process. Tarzan also obscures data traffic patterns by introducing cover traffic into the network to protect against an eavesdropper attempting to undermine the anonymity of the network.

Crowds is an anonymous communications system designed for anonymous Web browsing in which participants in the network are known as *jondos* (a la “John Doe”) [52]. An administrative process known as a *blender* assigns jondos to a crowd of other jondos and informs the new jondos of other members of the crowd.

When a participant’s browser first makes a Web request, his jondo establishes a random path through the network by first randomly picking another jondo (perhaps even itself) from the crowd and forwarding the request to it. That jondo then flips a biased coin and, depending on the outcome of the coin flip, the jondo either randomly selects another member of the crowd to which the request will be forwarded or forwards the request to the intended Web server. Each jondo also remembers the hop before it along the forwarding path, so that when a reply is received from the Web server the reply is relayed via the reverse of the established path. The pairwise connections between jondos are encrypted using shared keys assigned by the blender when a new jondo joins the crowd.

Tor is the most popular anonymous communications system in use and is known as the *second-generation onion router* due to the fact that it is based on, and makes several modifications to the original onion routing design in terms of security, efficiency, and deployability [17]. Tor uses a small set of trusted directory servers in order to distribute information about known onion routers in the network. In order to create a circuit, a Tor client iteratively negotiates session keys with each router along the circuit’s path using Diffie-Hellman key negotiation and one-way RSA authentication [17]. When a key is established with the first hop, the client can tunnel through that encrypted connection, establish a session key with the second hop, and so on. When a circuit is no longer used, the session keys are discarded, thus providing protection against replay attacks without the need to store the hash or ID of processed packets. Also, if an onion router is later compromised, the adversary is unable to recover previously used session keys.

For many anonymity networks, the anonymity service access points, typically the ingress nodes into the anonymous network, are publicly listed [17]. These ingress nodes (and egress nodes as well, for that matter) can be easily monitored by the adversary, and the attempt to establish anonymous communication is, therefore, not hidden. Thus, anonymity will not protect a user of the anonymity network from suspicion by the ISP or other powerful observing agent. If participating in such a network is sufficient to expose the participant, then the unlinkability provided by the network will not provide adequate protection. In such cases, membership concealment becomes critical.

2.4.3 DC Networks

A *Dining Cryptographer network* (DC-net) is a system also devised by David Chaum that provides *unobservability* [10]. Unobservability is a stronger property than anonymity in that an adversary monitoring the network is unable to distinguish messages carrying actual content and messages sent as random noise. Thus, the system conceals who is communicating with whom and hides which users sent or received a message during a period of observation.

In DC-networks, such as Herbivore or Xor-Trees [18, 23, 53], messages are broadcast to all members. Privacy is provided by the sharing of unique keys between pairs of members, and anonymity is provided by all members sending noise traffic when they have no message traffic. Thus, an observing party is unable to distinguish legitimate traffic from noise traffic or who is communicating with whom.

DC-nets generate a large signature due to the overhead of noise traffic. Thus, they become easy to identify when compared to normal Internet traffic. If an adversary can distinguish the traffic of the DC-net from other Internet traffic and identify even a single node within the overlay network, then by simply inspecting the IP headers of the identified node, other nodes are easily identified as well. Thus, if participation in such a network is sufficient for suspicion by the adversary, then DC-nets will not protect its participants.

2.5 Membership-Concealing Overlay Networks

Vasserman *et al.* describe *membership-concealing overlay networks* (MCON) [61], that is, networks where it is impossible (or, at least, very unlikely) for members inside the network or for third-party nodes to determine if a particular node participates in the communications of the network. Concealment with respect to other members of the network can be achieved where: (1) unlinkability and anonymity are provided through message forwarding; (2) trust relationships are minimized; and (3) network identities are replaced whenever possible with pseudonyms [61]. Concealment with respect to third-party nodes is provided by making the communication packets as indistinguishable as possible for all other network traffic, such as maintaining a low traffic footprint by using point-to-point communication and using common protocols that make the traffic harder to distinguish.

MCONs use pseudonyms and restrict their network topologies in such a way as to hide the identities of their members [61]. Assuming that traffic between participants in the overlay network is indistinguishable to an outside observer from all other traffic, MCONs restrict the number of nodes within the network that have knowledge of any single participants' real-world, network address. A network address can be the IP address–for networks that use direct point-to-point communication between neighbors, or other parameters for networks that use more sophisticated clandestine communication mechanisms such as fast-fluxing [43]. All other nodes are known only by a pseudonym denoting their logical address within the P2P network and their public key.

If the adversary can correlate a network address, such as an IP or email address, to a real-world identity, then membership concealment is compromised whenever the given network address is linked to the anonymity network. Membership concealment is implicit through the topology restrictions of the overlay network by restricting the number of connections that any single node may have to those that the user already has in the real-world. Thus, an MCON uses an an existing social network to bootstrap the communications topology of the overlay network. No participant "learns" the real-world identity of other MCON participants within the network.

2.6 Underground and Covert Networks

Motivated by considering the lines of communication within a terrorist cell, Gunther and Hartnell [27, 28, 30] propose a threat model for the type of covert communication networks examined here. Their threat model leads to so-called *neighborhood failures*, and the ability of the networks to survive k such failures is quantified as the *k-neighborhood connectivity* of the network. The authors identified several basic properties of k-neighborhood connected graphs and developed a method for constructing these graphs.

Lindelauf, Borm, and Hamers [38] propose a network topology that balances information efficiency (limiting the path distance between nodes) and network secrecy (limiting the danger of exposure). Thus, they primarily want to minimize the network diameter (the greatest distance between any pair of nodes) in order to reduce the probability that an adversarial node intercepts the message traffic, while also reducing the portion of the network that a compromised node can expose (by limiting the number of edges within the graph).

2.7 Delay-Tolerant Networks

Delay (disruption) tolerant networks (DTN) describe a general class of communications protocols designed to allow nodes within the network to successfully propagate reliable traffic despite intermittent connectivity [8, 20]. The DTN architecture was designed to accommodate not only network connection disruption, but also to provide a framework for dealing with the sort of heterogeneity found at sensor network gateways (and other gateways, more generally). DTN can use a multitude of different delivery protocols including TCP/IP, raw Ethernet, serial lines, or hand-carried storage drives for delivery. As each of these protocols provide somewhat different semantics, a collection of protocol-specific convergence layer adapters (CLAs) provide the functions necessary to carry DTN protocol data units (called bundles) on each of the corresponding protocols.

Though not often associated with anonymous and covert communication, DTN research is of particular interest for implementing resilient mix networks. Both DTNs and anonymity networks use intermediate nodes to route message traffic. Low-latency anonymity networks are vulnerable to traffic analysis attacks that can correlate message timing across the network and thus undermine the anonymity. Mix networks prevent these attacks by intentionally introducing additional latency. Thus, when latency is not a concern, DTNs can provide insight into implementing CCNs that protect anonymity and membership concealment while being resilient as well.

2.8 Conclusions

Each of the research areas discussed provides some form of protection to participants communicating with one another in the presence of an adversary. However, each on their own does not provide resilient networks with adequate protection against discovery of participants. We now examine covert communication networks which integrate aspects of the fields discussed above. In the following secions, we discuss the architecture and properties of covert communication networks and describe how they provide resilience, anonymity and membership concealment for their participants.

3. BASIC STRUCTURE AND OPERATION OF A COVERT COMMUNICATION NETWORK

Throughout this work we start from the premise that a peer-to-peer overlay of mix-like nodes is an appropriate basis for the development of a membership concealing, anonymous system. Given the peer-to-peer nature of such a system, the failure to protect any specific user affects the system as a whole, since the adversary may infer the membership of other users from the traffic emanating from the first victim to its peers. Mechanisms at multiple levels must be in place to protect the communication and the membership of participants.

Thus, we realize a CCN as a peer-to-peer overlay network, where traffic is routed from a source node to a destination node by relying on intermediate nodes to forward traffic through the network. Each participant acts, in traditional peer-to-peer manner, both as sender/receiver of data and as a router within the network. Two participants are *neighbors* in the CCN when they are directly connected to each other in the overlay topology with no intermediate nodes between them. Neighbor nodes in the CCN know of each other's *network address* (e.g., IP or email address) and neighbor-to-neighbor traffic is forwarded using whatever underlying transmission protocol has been negotiated by the nodes at join time. Nodes that are not neighbors never exchange traffic directly. Instead, messages are routed through intermediary nodes. Traffic is routed end-to-end through the network by using *logical addresses* and is forwarded through a sequence of neighboring nodes until the destination is reached.

[1]Portions of this section are reprinted with permission from "Subversion Impedance in Covert Communication Networks" by Timothy Nix and Riccardo Bettati, 2012, In *Proceedings of the 2012 IEEE 11th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom)*, pages 458-465, Copyright [2012] by IEEE.

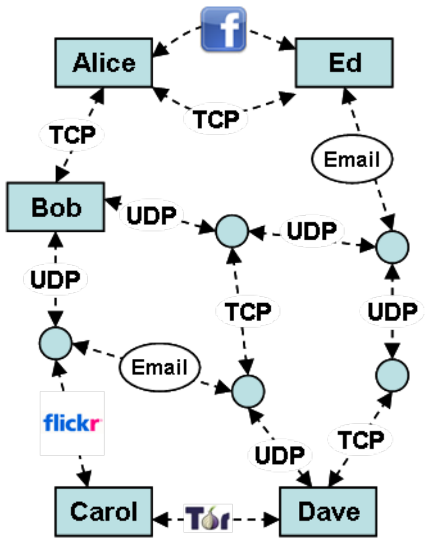


Figure 3.1: Example CCN

Figure 3.1 shows an example of a simple CCN with ten participants, four of which are identified by name. In this topology, Alice and Bob are neighbors within the overlay network. Thus, Bob has knowledge of Alice's network address. Bob is, however, unaware of the network addresses of any other nodes that are neighbors with Alice. If Bob receives a message from Alice, then either Alice is the source of the message, or Alice is forwarding the message from another source. Also, either Bob is the recipient of the message, or Bob forwards the message to his neighbor on the path to the message's destination.

3.1 End-to-end Communication

We assume that network addresses are assigned by an Internet Service Provider (ISP) which can correlate the address to a real-world identity. Thus, participants in a CCN restrict knowledge by other participants of their network address. We use *pseudonyms* as logical addresses within the network to provide an anonymous means for members to identify each other without revealing their network addresses.

Pseudonyms could be a unique username selected by the participant; a random string or set of digits; the participant's public key; or a numerical value associated with their location within the CCN overlay topology.

Pseudonyms are used by intermediate nodes to identify a message's destination. When a node receives data, it replaces the network address associated with the data, with its own network address and forwards the data to the next neighbor along the route. Thus, for each *message*, we have a source node, a destination node, and zero or more intermediate nodes that forward the message in a way as to delink the sender and the receiver.

3.1.1 Communication between Neighbors

Communication between neighbors in the CCN overlay is carried over what we call *channels*. Channels can be of different *channel types*, which in turn specify the implementation of each channel. Each channel type will have different performance characteristics in support of the communication requirements of the group. Different channel types can be easily developed based on the particular requirements of the group. For example, channels can be instantiated using: the *user datagram protocol* (UDP), the *transmission control protocol* (TCP), *simple mail transfer protocol* (SMTP) (i.e., email), covert channels, steganographic messages passed between nodes using either *file-transfer protocol* (FTP) or a shared repository (such as Facebook, Flickr, Twitter, etc.), or any other network communication protocol.

Channels are either *low-latency* or *high-latency*, each of which offers its own tradeoffs between performance and anonymity. Low latency communication provides near-real-time communication for group members at the risk of providing an adversary with timing signatures for tracing packets across the overlay network, thus undermining anonymity. If near-real-time communication is not required, then nodes can provide the full functionality of a mix by both batching messages and introducing variations in timing to obscure communication signatures and increase anonymity.

A node may have multiple channels from which to choose in order to transmit data to a particular neighbor. The channel type used to communicate between neighbors is negotiated as part of the join protocol of a new node, and the channels used by the network are instantiated at each node immediately after joining the network and selected for use based on the requirements of each specific message.

In Figure 3.1 Alice had two neighbors: Bob and Ed. In one case, Alice communicates through Bob using a TCP channel, and communicates through Ed using either a TCP channel or Facebook. Facebook, Flickr and other social network and file sharing sites can be used to pass messages embedded in photos or music files using standard steganographic techniques. Alice needs only to provide Ed with the account and filename to successfully pass the message. Thus, Alice can send data to Ed in more than one way. For latency-sensitive communication, they can select to use the TCP channel, while the Facebook channel can be used for the remaining communication.

During establishment of the overlay network (typically as part of the join protocol discussed in Section 8) neighboring nodes discover and negotiate the set of channels to be provided. During the connection establishment, each node selects from among the available channels the particular channel to be used on the outgoing link to the next node in the overlay network.

3.1.1.1 Pushing vs. Pulling Data

As in most peer-to-peer networks, each node in the CCN operates as both a *server* and a *client*. We make the distinction between the two by denoting the client as the process that initiates the communication. Data can be pulled or pushed by a channel, as necessary. In the first case, when the channel receives a message, the message is buffered until it is requested by the appropriate neighbor. The process is repeated at each node, propagating across the network until the data packet reaches its destination. In the second case, when a node receives data that needs to be forwarded, the node automatically connects to the appropriate neighbor and forwards the message.

The polling of adjacent nodes provides a basis for message batching and timing disruption. These are two key characteristics of early Mix networks [13]. However, the timing of the polling could potentially provide a signature that would undermine membership concealment. Randomizing the time periods between polls would disrupt the timing and provide protection against these types of attacks.

Message pushing, on the other hand, minimizes propagation delay between adjacent nodes if the message is sent immediately. If messages are also routed along the fastest route, then the source-to-destination propagation delay is minimized. This is essential when near-real-time communication is necessary, such as voice-over-IP (VoIP) or video teleconferencing.

3.1.2 Pseudonyms

Pseudonyms are identifiers that should not be linkable to the real identities of the participants. In other words, a pseudonym is an identifier of a subject other than one of the subject's real names [53]. Thus, pseudonyms provide a means for non-adjacent nodes within a covert communication network to communicate with each other without needing to share their network addresses.

Pseudonyms could be a unique username selected by the participant, a random string or set of digits, the participant's public key, or a numerical value associated with their location within the CCN overlay topology. Participants distribute their pseudonym as a means for other nodes to communicate with them. In our implementation, pseudonyms correspond to a logical location within the network topology in order to facilitate routing.

3.1.3 CCN Message Confidentiality

Cryptography provides message confidentiality. Though orthogonal to anonymity and membership concealment, confidentiality is an inherent requirement in a CCN. Given the threat model, we use cryptography to guard message confidentiality.

Thus, all traffic within the CCN is encrypted. Encryption occurs at two levels. First, we have end-to-end cryptography where the source encrypts the payload so that it is only readable by the destination. Second, we have hop-level cryptography, where a node along the route encrypts the data packet so that it is only readable by the next node along the route. Since messages are also re-encrypted every time they are forwarded by a node, this also provides protection against the adversary tracing messages across the network.

CCNs can use either symmetric or asymmetric cryptography. Similar to other Internet protocols such as transport layer security (TLS), symmetric cryptography is used for low-latency communication. For exchanging symmetric keys, asymmetric cryptography is used. It can also be used for encrypting and decrypting delay-tolerant traffic.

Public keys are shared in a distributed manner among the CCN nodes via a *web of trust*. In the web of trust, keys propagate across the network as they are shared from neighbor to neighbor. As long as two or more paths exist between any two nodes, attempts to corrupt public keys or execute a man-in-the-middle attack are detectable. Thus, there is no need for a central certificate authority.

3.2 Topology Considerations

The ability of a CCN to protect the identity of participants depends to a large extent on the connectivity between nodes who posses the network address of each other. Most, if not all, of the research conducted on underground, covert and membership concealing networks to date has therefore focused on the *topology of the network* [30, 38, 61]. The idea behind these topologies is to minimize the damage done by the subversion of a node. Gunther and Hartnell [30] examined network topologies that either maximize the number of survivors in the event of the deletion of a closed neighborhood of nodes; or are resilient (i.e., remain connected) from multiple subversions. In the first case, they found various tree structures to be optimal. In the second, they demonstrated a construction for k-neighbor-connected graphs; that is, graphs that remain connected from the removal of k closed neighborhoods of nodes.

Lindelauf *et al.* [38], on the other hand, examined topologies that optimized the trade-off between: (1) minimizing the number of edges that a message must travel and, thus, the probability that a message is intercepted by an adversary (thus, increasing node degree); and (2) minimizing the number of nodes that any subverted node might compromise (thus, decreasing node degree). They found that complete graphs provided the optimal solution in low threat areas, i.e., low probability of node subversion; whereas, the star graph and a cellular network provided the optimal topology for conditions with a higher probability of subversion. Unfortunately, the complete graph does not provide membership concealment in that any participant has knowledge of all other participants' network addresses. Star graphs are not resilient against disconnection. Rather, CCN topologies need high connectivity for resilience but must also be as sparsely connected as possible in order to protect membership concealment.

3.2.1 Threat Model

Our network participants, Alice and Bob, are legitimate members of the CCN. We assume that Alice and Bob wish to communicate over the covert communication network. Eve is the powerful adversary attempting to gain information about the covert communication network and identify its participants. If Eve learns the network address of either Alice or Bob, we consider this information sufficient and necessary to then identify Alice's or Bob's real-world identity. For example, if Eve learns a participant's IP address using the ISP database, she can determine the owner of the IP address and then use this information to identify Alice and Bob.

We define Bob's *network promiscuity* as the number of other participants that have knowledge of his network identity. Then, Bob's membership concealment is reduced in proportion to his network promiscuity. The more participants that have knowledge of Bob's network identity, the higher the probability that the adversarial node Eve knows Bob's network identity and can, thus, correlate his network identity to his real-world identity.

In our threat model, a node is *subverted* when Eve successfully attacks the node. A node might be subverted in a variety of ways: Either Alice or Bob could betray the group and switch to the side of the adversary, Eve. Similarly, Eve could infect a node in a way that allows her to monitor communications across this node. Finally, Eve could infiltrate the network by successfully joining. Nodes attached to the betrayed node are then considered *compromised* because their owners might be identified by their network address. The subverted node can directly monitor communications with the compromised nodes and can provide this information to the adversary.

If a node is suspected of being subverted, then both the node and all connected nodes are removed from the network: either the owners of the compromised nodes are arrested, or the network membership successfully identifies the subverted node and disconnects from it and its compromised neighbors. This particular threat model was used by Gunther and Hartnell in their examination of the communication topologies of underground resistance movements (covert communication networks) [30]. With no loss of generality, we treat the subversion of multiple nodes as separate events.

3.2.2 Network Resiliency

We want our network to be resilient against partitioning. In the event of the subversion of a node and the compromise of its neighbors, we want to maximize the chance that the network remains connected.

Therefore, we want a network topology that minimizes the number of nodes that will potentially connect to Alice. This way, if Alice's node becomes subverted, then the number of compromised nodes is also minimized. However, we also want a network topology that is resilient against disconnection through the removal of multiple neighborhoods of nodes.

As long as connectivity cost is not an issue, the effect of single-node failures in traditional networks can be easily countered by making networks more dense. A *fully-connected* or *complete* network is a communication network in which every pair of nodes is adjacent. Such a complete network provides (1) the shortest path length between any two nodes minimizing communications time; and (2) the highest degree of path redundancy and protection against network partition. If we were only concerned over the loss of a single node in the event of a subversion, then the connectivity of the surviving network would decrease by one, and the network would remain connected for any graph with more than two nodes. Given our threat model, the problem with a complete graph, of course, is that the subversion of any single node results in the compromise of the entire network.

On the other hand, a *tree* is an undirected graph in which any two nodes are connected by exactly one simple path. If minimizing connectivity were our only concern, then a tree would be the ideal structure since it provides a communications path between all nodes while minimizing the order of each node, and thus, the damage resulting from the subversion of any node. In [30], Hartnell and Gunther initially focus on several types of trees as being resilient to subversions. In a tree-like network topology, however, the subversion of any node may lead to a partitioning of the network. The surviving components would then be unable to communicate with each other.

The above examples illustrate that covert communication networks must naturally balance the level of connectivity of nodes against the size of their neighborhood. They must be highly connected in order to be resilient against disconnection. They must also be as sparsely connected as possible in order to minimize network promiscuity.

Network resiliency also provides multiple paths between nodes. Thus, traffic could still be routed even if some portion of the nodes were down. We can also use network resiliency to detect attempts by an adversary to corrupt network traffic. Copies of the same message could be sent along different paths. These copies could then be compared by the destination node to ensure message integrity and identify subverted nodes that may attempt to modify packets. However, if not strictly managed, this approach could result in a significant amount of traffic creating an easily identifiable signature to an adversary.

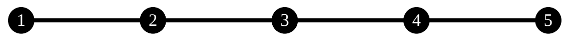


Figure 3.2: Path topology on 5 nodes, P_5

3.2.3 Deterministic versus Random Topology Construction

Deterministic topologies are those in which the direct connections established within the topology are deterministic. Thus, the topology of the network is defined as a function of the number of nodes. A given node within the network might have been located at a different point within the topology if it had joined at a different time, but the overall topology for a given number of nodes remains the same. Figure 3.2 shows a simple path topology on 5 nodes. An example of a deterministic construction for a path topology on n nodes is one in which Node v_n connects to the next node that joins, v_{n+1}.

Random topology constructions are those in which, as new nodes join the network, neighbor connections are randomly determined. Thus, even the topology of two different overlay networks with the same number of nodes is likely to be different.

3.2.4 Structured versus Unstructured Topologies

In a structured topology, the location of the participant in the covert communication network (not to be confused with the network address within the larger network) is arranged and assigned in a structured manner. Chord [57] and CAN [51] rely on a random but structured topology to facilitate node joins and data lookup. In Chord and CAN, a node's logical location within the overlay network can be considered the node's pseudonym. As we will see in Section 4 and Section 5, the k-neighbor-connected networks constructed by Gunther and Hartnell [30] and the characteristics of cages can be used as structured topologies. As we will see in Section 8, pseudonyms can be structured as logical addresses, indicating where in the overlay topology a node is located and, thus, facilitate routing.

In unstructured topologies, pseudonyms do not correspond to a node's logical address within the topology. Thus, nodes must advertise their logical address to other nodes to facilitate routing. This can be done easily using traditional network approaches to node discovery, but it does increase the communication signature of the network and the complexity of each node.

3.3 Communications Considerations

Though many of the same principals that we have discussed thus far can apply to a variety of communication networks, we have defined CCNs as an overlay network. We now examine the rationale behind this decision and some other design choices with regard to CCNs as overlay networks.

3.3.1 No Specialized Equipment Required

Concealed communication can be established using specialized technology, such as spread-spectrum transmitters. However, in practice, use of such additional hardware comes at a cost; it has to be acquired, distributed, maintained, and, in many cases, possession of the specialized equipment is enough to compromise membership anonymity. Thus, specialized equipment limits who can participate in the network.

In contrast, computers are becoming more and more common in most countries. Ownership of a computer is usually not suspicious. This also allows the covert communication network to be implemented in software at the application level with low signature for detection. Techniques used to conceal computer viruses can also be used to further conceal and obfuscate the presence or purpose of the covert communication network application, such as embedding the communication software within another benign application.

3.3.2 Open versus Closed Infrastructure

An *open infrastructure* does not require participants to be actual members of the network. If Bob wants to participate in the covert communication network but does not want to join the network, then he will need to use an actual member node as an entry point into the network. Likewise, if Alice is the recipient of Bob's message, and she is not a member of the network, then a member node will need to be used as an exit point from the network to Alice. In either case, the fact that Bob and Alice participate in the system is known to the entry and exit nodes, respectively. Open infrastructures leave both the entry and exit nodes of the network and the participants vulnerable: on the one hand, the entry and exit nodes in an open infrastructure are likely to connect to many participants; and on the other hand, participants might have to establish connections (or "tunnels") through potentially large numbers of entry and exit nodes, making it known to them that the participants are engaging in covert communication. If participants use the same entry and exit points each time, they limit their own exposure, but their lack of membership in the network as router nodes reduces the potential resiliency of the network. If all members act in this manner, the result is a network with no intermediate nodes providing anonymity.

A *closed infrastructure* provides a higher degree of anonymity for all nodes. If Alice and Bob are members of the network, then a node adjacent to and receiving a message from Alice will not know whether she is the originator of the message, or simply another link in the routing chain. Furthermore, no nodes are required to serve as entry or exit nodes and, thus, consistently connecting to new nodes. As a result, any covert communication network that gains anonymity and unlinkability by using network members as mixes, onion routers, etc. requires a closed infrastructure.

We note that this distinction in effectiveness between open and closed infrastructures is quite common: for example, reliable multicast protocols come in open and closed forms, and it is a well-known fact that closed infrastructures are more reliable. These benefits come at the cost of having to explicitly maintain the membership in the network.

3.3.3 Decentralized Control

The history of P2P file sharing networks such as Napster, Gnutella, Chord and CAN [26, 51, 57] has shown that distributed control mechanisms are superior to centralized control mechanisms which limit reliability and scalability. It also limits membership concealment. For example, Tor relies on the public list of onion routers that allow participants to build their circuits through the network [17]. Thus, a powerful adversary might be able to monitor traffic at a network firewall or ISP gateway and identify packets destined for Tor and learn the identities of participants. The *Distributed Hash Table* (DHT) in Chord provides a means to store pseudonyms and public encryption keys in a decentralized manner within a P2P network. Coupled with a structured network organization, a DHT provides a mechanism for information lookup and retrieval within a P2P network and has no single point of failure.

Both of these structures grow by inserting new nodes into the existing network topology. Though a given node may have a limited number of neighbors to which it passes message traffic, it will have been connected to a larger number of nodes throughout this lifetime. For example, if a new node is inserted "between" Alice and Bob, Bob will "forget" Alice's network address and retain the network address of the new node. This works fine in most cases, but in a covert communication network where we must limit Bob's network promiscuity, this approach will not work. If Eve successfully infiltrates the network, then there is no limit to the number of network participants that she will compromise as long as she remains a member. Instead, in a covert communication network, we must constrain the network promiscuity of all nodes over their lifetime.

Thus, we want decentralized control in a covert communication network. DHTs would provide a mechanism for storing pseudonyms and their associated cryptographic keys. However, we must restrict dynamic aspects of P2P networks in ways that fix the network promiscuity and maximize the anonymity of participants.

3.3.4 Effects of Network Promiscuity and Trust

Increasing network promiscuity by revealing one's network address to another node reduces membership concealment and increases the probability of compromise in the event of a subversion. Thus, members are more likely to be willing to reveal their network address to a participant that they already know rather than to a stranger. Vasserman *et al.* [61] use out-of-network, personal relationships with which to build MCONs. This is due to the inherent risk associated with revealing one's network address to a participant that is also a stranger. Revealing one's network address to another is a statement of trust.

3.4 Conclusions

The research community is increasingly becoming aware that traditional sender-receiver anonymity measures are not sufficient to participants in anonymity systems. Rather, membership concealment and concealment of anonymity infrastructure itself are important when stakes are high and/or when the anonymity infrastructure cannot escape a global adversary deployed across multiple jurisdictional domains.

In this section, we examined essential requirements and design choices for covert communication networks. By definition, trust entails a component of risk. In some circumstances, use of a covert communication network is a life-and-death decision. Thus, the network should not induce more risk than absolutely necessary. Covert communications networks attempt to minimize this risk while providing participants with a resilient communications network that provides privacy, anonymity, and membership-concealment. This type of network is promising for high risk situations. We now examine the trade-off between resilient topologies and membership-concealment in order to find topologies that are suitable for CCNs.

4. TOPOLOGY MEASUREMENT IN COVERT COMMUNICATION NETWORKS

As discussed in Section 3.2.2, the design of a resilient network for covert communication requires the careful trade-off between minimizing the number of nodes affected by the presence of a subverted node (we denote this as *secrecy*) and maximizing the resilience of the network to remain connected despite multiple subversions (we denote this as *resilience*). In the following, we develop a measure that integrates both *secrecy* and *resilience* in order to determine the topology of a resilient covert communications network. Appendix A provides an overview of the graph theoretic terms and symbols used in the following sections.

In [37, 38], Lindelauf et al. define a topology performance measure on a graph, G,

$$\mu(G) = S(G)I(G) \quad ,$$

where $S(G)$ is the *secrecy measure* and $I(G)$ is the average performance of the network. The average performance, $I(G)$, is defined by the (normalized) reciprocal of the total network distance. Thus, topologies with high average performance have shorter distances between nodes with the best performance being a fully-connected network. Their secrecy measure is defined as

[2]Portions of this section are reprinted with permission from "Subversion Impedance in Covert Communication Networks" by Timothy Nix and Riccardo Bettati, 2012, In *Proceedings of the 2012 IEEE 11th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom)*, pages 458-465, Copyright [2012] by IEEE.

[3]Portions of this section are reprinted with permission from "Topology Construction of Near-Optimal Covert Communications Networks" by Timothy Nix and Riccardo Bettati, 2012, In *Proceedings of the 2012 International Symposium on Pervasive Systems, Algorithms, and Networks (ISPAN)*, pages 135-142, Copyright [2012] by IEEE.

$$S(G) = \sum_{i \in V} \alpha_i(G) u_i(G) \quad ,$$

where $\alpha_i(G)$ is the *a priori* probability that upon surveillance individual i will be exposed as a member of the network, and u_i is the fraction of the network that remains unexposed when i is detected.

Our approach is similar to Lindelauf *et al.* [38] in that we optimize two competing requirements. Furthermore, we borrow their *secrecy* measure though we modify it for our given threat model. The secrecy measure used by Lindelauf examines the proportion of nodes that remain after the subversion of a node. However, their secrecy measure incorporates the probability that each given node within the network is subverted. This provides an interesting degree of freedom within the design space, allowing them to calculate their measure based on the *a priori* probability distribution of node subversions.

The *a priori* probability distribution of node subversion quantifies the realistic probability of subversion associated with each node. However, it is difficult, if not impossible, to assign meaningful probability values to each node. The *a priori* probability distribution reflects the behaviors of the network members and is constantly changing based on those behaviors. However, meaningful analysis can be done by simplifying the *a priori* probability distribution for subversion to either the worst-case, as we show in the Section 4.1, or a uniform case, as we show later in Section 5.

4.1 Global Subversion Impedance

Definition 4.1.1. *We define our* **secrecy measure***, S, to be the proportion of the* nodes *that survive the subversion of node $v \in V$. In other words, $S(G, v)$ is the order of the survivor graph, $|H(G, v)| = |G - N[v]|$ divided by the order of the original graph, $|G|$. Recall that the subversion of node v ensures that both v and its* *neighborhood, $N(v)$, is affected. Thus,*

$$S(G,v) = \frac{|H(G,v)|}{|G|} \quad . \tag{4.1}$$

We assume that $|G| > 3$ and G is connected. In the worst case, when G is complete, $G = N[v]$, so $S(G,v) = |G - N[v]| = 0$. In the best case, if v is a leaf and $deg(v) = 1$, then $|N[v]| = 2$.

Definition 4.1.2. *We define our* **resilience measure***, K, to be the proportion of the* connectivity*, κ, that survives the cut of $N[v]$. In other words,*

$$K(G,v) = \frac{\kappa(H(G,v))}{\kappa(G)} \quad . \tag{4.2}$$

Again, we assume G is connected and, thus, $\kappa(G) \geq 1$. In the best case, κ is not reduced after removing $N[v]$; for example by removing a leaf and adjacent node in any linear graph, so $K(G,v) = 1$. In the worst case, when G is a complete graph, then $K(G,v) = 0$, or if the cut of $N[v]$ produces a disconnected graph, then the result is $\kappa(H(G,v)) = 0$.

Definition 4.1.3. *We call the* **local subversion impedance** *of a covert communications network G on node v as $\gamma(G,v)$, where:*

$$\gamma(G,v) = S(G,v)K(G,v) \quad . \tag{4.3}$$

We are interested in network topologies that have a high $\gamma(G,v)$ in the worst case. So, we must first examine the worst case for a given graph. We denote v^* as the node in a graph, G, such that the cut of v^* and its neighborhood minimizes the local subversion impedance of the network G:

$$v^* = argmin\{\gamma(G,v) \mid \text{for all } v \in V\} \quad . \tag{4.4}$$

Thus, v^* can be thought of as the node whose subversion has the worst-case effect on the covert communication network. The effect of subverting v^* in G is the (global) subversion impedance of the network G.

Definition 4.1.4. *The* **(global) subversion impedance** *of a covert communications network G is $\gamma^*(G)$, where:*

$$\gamma^*(G) = \gamma(G, v^*) = \min_{v \in V} \gamma(G,v) \quad . \tag{4.5}$$

If any subverted node in G produces a disconnected graph, then $\gamma^*(G) = 0$. We refer to the worst-case survivor graph as $H^*(G) = H(G, v^*)$. Thus,

$$\gamma^*(G) = \frac{|H^*(G)|}{|G|} \times \frac{\kappa(H^*(G))}{\kappa(G)} \quad . \tag{4.6}$$

Finally, consider the set of all graphs of a given order, n, which we denote $\mathbb{G}^n$.

Definition 4.1.5. *We call the graph $G^n_{opt} \in \mathbb{G}^n$ an* **optimal covert communications network (OCCN)** *if $\gamma^*(G^n_{opt}) \geq \gamma^*(G)$ for all $G \in \mathbb{G}^n$.*

Definition 4.1.6. *We call the* **optimal subversion impedance** *of all graphs in $\mathbb{G}^n$ as $\Gamma(n) = \gamma^*(G^n_{opt})$. Formally,*

$$\Gamma(n) = \max_{G \in \mathbb{G}^n} \gamma^*(G) \quad .$$

Thus, given our subversion impedance, we now have a way to quantify the suitability of a covert communications network on n nodes; that is, for a network to tolerate neighborhood subversions. However, identifying optimal graphs with naïve approaches, such as enumeration, is infeasible even for graphs with relatively few nodes. For example, there are approximately 10^9 different connected graphs of order $|G| = 12$ (see [56]). So, any search quickly becomes infeasible. Instead, we examine $\Gamma(n)$ to determine characteristics of the desired network topology in order to more systematically construct neighborhood-failure tolerant networks.

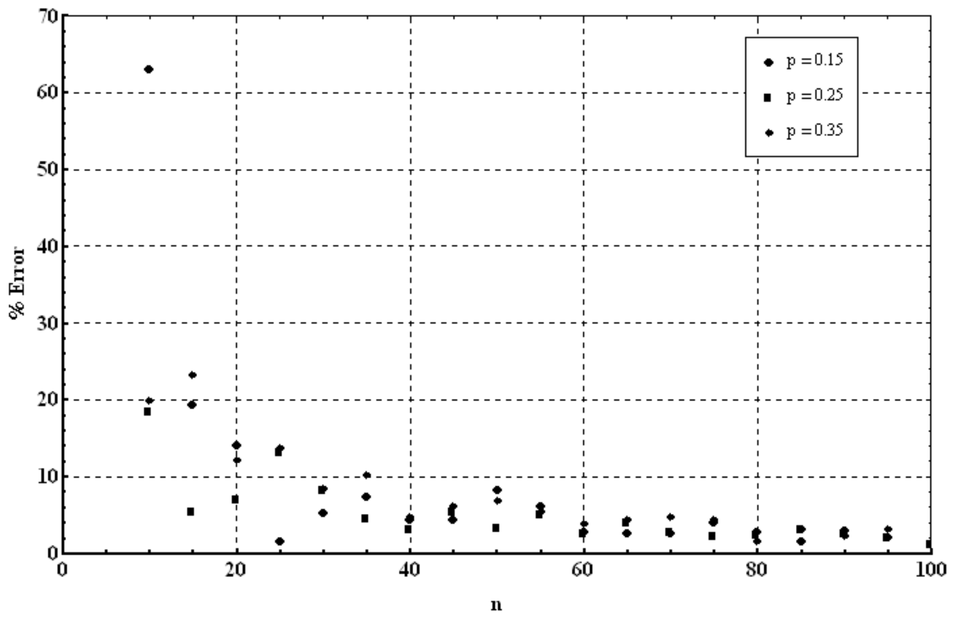


Figure 4.1: Plots of the anticipated $\gamma^*(G)$ for *k-regular, k-connected* $G \in \mathbb{G}^n$ with $girth(G) \geq 5$ (should it exist) for each k and each n.

4.2 Optimal Covert Communications Network Topology

We want the risk of compromise to be as evenly distributed across the network as possible. Given that the risk of compromise is proportional to the network promiscuity, this implies that every node within the network should have the same number of neighbors. In order to find graphs that optimize both secrecy and resilience, we focus on *k-regular, k-connected* graphs. This makes sense from an operational perspective, since we want the risk of being affected by a subverted node to be distributed as evenly across the participants as possible. Also, it simplifies our analysis.

For *k-regular, k-connected* graphs, we can precisely determine the *connectivity* and *order* of the worst-case survivor graph. In the following, we show that a large-enough girth of a *k-regular, k-connected* graph will ensure that the minimum degree in the worst-case survival graph is only one less than the minimum degree in the original graph; that is, $\delta(H^*(G)) = \delta(G) - 1$. For *k-regular, k-connected* graphs, this also minimizes reduction in the connectivity and so helps overall resilience.

Lemma 4.2.1. Given a *k-regular, k-connected* graph G with $girth(G) \geq 5$, the worst-case survivor graph has a minimum degree of $\delta(G) - 1$. In other words,

$$\delta(H^*(G)) = \delta(G) - 1 \quad . \tag{4.7}$$

Proof. We prove Lemma 4.2.1 by showing that, given a graph $G = (V, E)$ with $girth(G) \geq 5$, the high girth means that multiple nodes in the same neighborhood are not adjacent to a node that is not in the neighborhood. So, let $\{v_1, v_2\} \in N(v_o)$. Then $v_1 v_o v_2$ is a path. If $v_3 \notin N[v_o]$ is adjacent to v_1 then the path becomes $v_3 v_1 v_o v_2$ and cannot be adjacent to any other nodes in $N[v_o]$ (otherwise a 4-cycle would exist, which contradicts our assumption that $girth(G) \geq 5$). Thus, in the survivor graph, v_3 has lost, at most, one edge. Since G is *k-regular, k-connected*, then by Equation A.2, in G, $deg(v_3) = \delta(G)$, whereas in $H^*(G)$, $deg(v_3) = \delta(H^*(G)) = \delta(G) - 1$. □

Lemma 4.2.2. If G is *k-regular, k-connected* with $girth(G) \geq 5$, then the connectivity of the worst-case survivor graph is $k - 1$. More formally,

$$\kappa(H^*(G)) = \delta(G) - 1 = k - 1 \quad . \tag{4.8}$$

Proof. Let G be *k-regular, k-connected* with $girth(G) \geq 5$. Then for every node, each edge corresponds to an independent path to all other edges. Removing $N[v]$ means removing, at most, one edge from nodes within the surviving graph, and from Lemma 4.2.1, $\delta(H^*(G)) = \delta(G) - 1$. For each of those nodes v_i that lost one adjacent node, all remaining edges still correspond to an independent path to all remaining nodes. Therefore, $\kappa(H^*(G)) = deg(v_i) = \delta(H^*(G)) = \delta(G) - 1$. Since this holds true regardless of the node v selected, it hold true for v^*. Thus, $\kappa(H^*(G)) = \delta(G) - 1 = k - 1$. □

Lemma 4.2.3. If a graph G with order n is *k-regular, k-connected*, then the order of the worst-case survivor graph is $n - k - 1$. Formally, we say

$$|H^*(G)| = |G| - \delta(G) - 1 = n - k - 1 \quad . \tag{4.9}$$

Proof. Let G be *k-regular, k-connected.* Then every node $v \in V$ has a $deg(v) = \delta(G) = \Delta(G) = k$. Removing $N[v^*]$ means removing $k + 1$ nodes from the original graph G to create the survivor graph $H(G, v)$. Since this holds true regardless of the node v selected, it hold true for v^*. Thus, $|H(G, v)| = |H^*(G)| = |G| - \delta(G) - 1 = G - k - 1$. □

Corollary 4.2.1. Assume a *k-regular, k-connected* graph G of order n with $girth(G) \geq 5$ exists, then the subversion impedance of G is

$$\gamma^*(G) = \frac{n - k - 1}{n} \times \frac{k - 1}{k} \quad . \tag{4.10}$$

Figure 4.1 plots the subversion impedance for *k-regular, k-connected* graphs with $girth(G) \geq 5$ as a function of the graph order for increasing values of k. Each plot represents a different value for $k = \{2, 3, 4, 5, 6\}$ using Equation 4.10 from Corollary 4.2.1. The optimal subversion impedance $\Gamma(n)$ is the maximum $S(G)K(G)$ possible for a given n. Note that, we are not guaranteed that a *k-regular, k-connected* graph exists if $k > 2$. However, in the following, we use the plots from Equation 4.10 to determine the bounds on the optimal subversion impedance $\Gamma(n)$ for *k-regular, k-connected* graphs of order n, and thus, for arbitrary graphs of order n.

Lemma 4.2.4. For all *k-regular, k-connected* graphs, $G \in \mathbb{G}^n$ with $girth(G) \geq 5$,

$$\Gamma(n) \geq \frac{n-3}{2n} \quad .$$

Proof. For all $n \geq 5$, a cycle, C_n, can be constructed. Since C_n is *2-regular, 2-connected*, by Corollary 4.2.1,

$$\gamma^*(C_n) = \frac{n-3}{2n} \quad .$$

Then, using Definition 4.1.6, we know that the optimal *k-regular, k-connected* graph has a γ^* at least as large. Thus, $\Gamma(n) \geq \gamma^*(C_n)$ gives a lower bound on $\Gamma(n)$. $\square$

We see in Figure 4.1 that, as the order n of the graphs increases, the values of k that provides the highest $\gamma^*(\cdot)$ also increase in a stepwise manner. Thus, we can use Equation 4.10 as a means for quantifying the upper bound of $\Gamma(n)$. We generate the value for the optimum k (hereafter denoted as k^*) for the specific ranges of graph order by calculating $\gamma^*(G)$ for various k and then selecting

$$k^* = \arg\max_k \gamma^*(G).$$

Theorem 4.2.1. For all *k-regular, k-connected* graphs G of order n, the upper bound of the optimal subversion impedance $\Gamma(n)$ is

$$\gamma^*(G) \leq \frac{n-k^*-1}{n} \times \frac{k^*-1}{k^*} \ ,$$

with

$$k^* = \left\lceil \frac{-1+\sqrt{4n-3}}{2} \right\rceil \quad . \tag{4.11}$$

Proof. In order to determine when k^* increases, we examine Figure 4.1. We need to determine the transition points on the curves where k^* increases by 1 to maintain the optimal value $\Gamma(n)$. At these points, using Equation 4.10, we get,

$$\left[\frac{n-k^*-1}{n}\right]\left[\frac{k^*-1}{k^*}\right] = \left[\frac{n-(k^*+1)-1}{n}\right]\left[\frac{(k^*+1)-1}{k^*+1}\right] \quad .$$

Solving for k^* and recognizing that k^* must be a positive integer gives us,

$$k^* = \left\lceil \frac{-1+\sqrt{4n-3}}{2} \right\rceil \quad .$$

Thus, we can solve for k^* as a function of the graph order, n, in order to determine the upper bound of $\Gamma(n)$. □

Corollary 4.2.2. For a given k with $k \in \mathbb{N}$ and $k \geq 2$, the order, n, of an optimal graph is bounded by:

$$k^2 - k + 2 \leq n \leq k^2 + k + 1 \tag{4.12}$$

Theorem 4.2.2. A *k-regular, k-connected* graph G with order n,

$$k = \left\lceil \frac{-1+\sqrt{4n-3}}{2} \right\rceil$$

and $girth(G) \geq 5$ is an *optimal covert communications network (OCCN)* on n nodes (i.e., $G = G^n_{opt}$).

Proof. Given a graph G that is *k-regular, k-connected*, then by Corollary 4.2.1, we know that $\gamma^*(G)$ is determined by Equation 4.10. Assuming k is determined from Equation 4.11, then from Theorem 4.2.1, the upper bound of $\gamma^*(G)$ is also determined by Equation 4.10. Thus, the value for $\gamma^*(G) = \Gamma(n)$ the upper bound. So, by Definition 4.1.5. G is an OCCN. □

With the groundwork laid out in this section, we proceed to define engineering guidelines for the design of resilient covert communication networks in the next section. We start by looking for a class or family of graphs that are *k-regular, k-connected* and $girth(G) \geq 5$.

4.3 Examples of Optimal Graphs

Following the previous discussion, we focus our attention to *k-regular, k-connected* graphs with $girth(G) \geq 5$. A particularly interesting family of such graphs are so-called *cage graphs.*

4.3.1 Girth-5 Cages

A $(k; girth)$-*graph* is a *k-regular* graph with the given *girth.* A $(k; girth)$-*cage* is a $(k; girth)$-*graph* with the smallest possible order. Fu, *et al.* have proven that all cages are at least 2-connected, all cubic cages $(3, girth)$-*cage* are 3-connected, and conjectured that all simple $(k; girth)$-*cages* are k-connected [22]. Thus, we first look to $(k; girth)$-*cages* in order to find G^n_{opt}.

First, we examine the unique $(3; 5)$-*cage*, better known as the *Petersen graph* [66], shown in Figure 4.2. As expected, it is *3-regular* and *3-connected* with $girth(G) = 5$, and order $|G| = 10$. If $N[v^*]$ is removed from this graph, the result is the induced subgraph shown on the right in Figure 4.2. In this case, the survivor graph con-

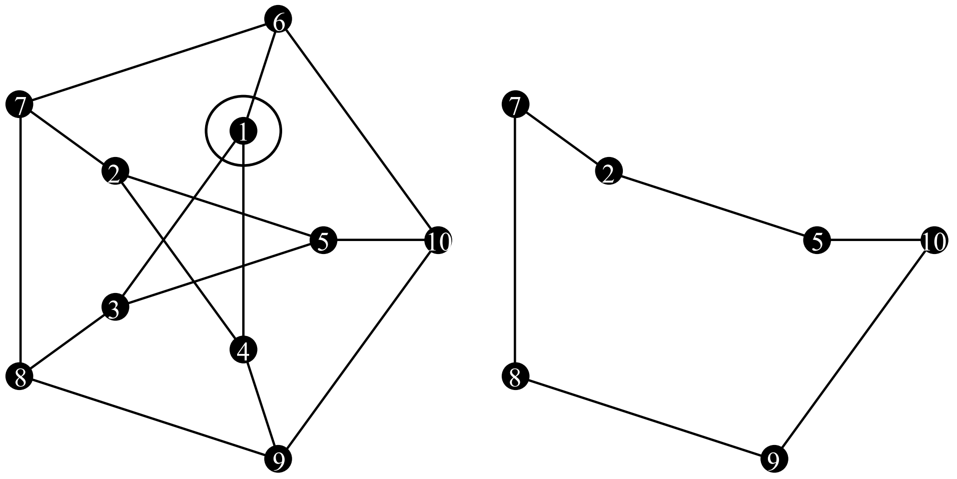


Figure 4.2: $(3;5)$-*cage* - The Petersen graph and associated survivor graph

sists of a single 6-cycle, which is 2-connected. From Corollary 4.2.1, we calculate its subversion impedance and compare it to the optimal subversion impedance by Theorem 4.2.2,

$$\gamma^*(G) = \frac{6}{10} \times \frac{2}{3} = \frac{2}{5} = \Gamma(10) \quad .$$

Thus, the $(3;5)$-*cage* is an OCCN.

Next, the unique $(4;5)$-*cage*, known as the *Robertson Graph*[66] is, as expected, 4-regular and 4-connected with *girth* $= 5$, and order $|G| = 19$. If $N[v^*]$ is removed from this graph, the resulting worst-case survivor graph has an order of 15 and connectivity of 3. From Corollary 4.2.1 and Theorem 4.2.2:

$$\gamma^*(G) = \frac{14}{19} \times \frac{3}{4} = \frac{21}{38} = \Gamma(19) \quad .$$

Thus, the $(4;5)$-*cage* is an OCCN.

There are four different $(5;5)$-*cages* [66]. Each of the four different $(5;5)$-*cages* are 5-regular and 5-connected with $girth = 5$, and $|G| = 30$. Thus, the the graphs are not isomorphic but they each have the same subversion impedance. In this case, the order of the survivor graph is 24 and its connectivity is 4. From Corollary 4.2.1 and Theorem 4.2.2:

$$\gamma^*(G) = \frac{24}{30} \times \frac{4}{5} = \frac{48}{75} = \Gamma(30) \quad .$$

Thus, the $(5;5)$-*cage* is an OCCN.

We can apply the same measurements to the unique $(6;5)$-*cage*, known as the *Foster Cage*[66], and the unique $(7;5)$-*cage*, known as the *Hoffman-Singleton Graph*[66]. In both cases, since the cages are *k-connected, k-regular*, they measure as OCCNs.

Not all cages of the same order are optimal. We illustrate this by comparing the subversion impedance, $\gamma^*(G)$, of two cages of the same order ($n = 30$). The $(3;8)$-*cage* is not optimal, while the $(5;5)$-*cage*, with its higher connectivity, is optimal.

$$\gamma^*((3;8)\text{-cage}) = \frac{26}{45} < \frac{48}{75} = \gamma^*((5;5)\text{-cage}) = \Gamma(30) \quad .$$

In practice, cages with $girth(G) > 5$ will not have the same level of connectivity that the $girth(G) = 5$ cages will. By Theorem 4.2.2, any cage is not optimal unless its value for k is appropriate for its *order* (Equation 4.11).

Since we have seen that all of the known $(k;5)$-*cages* are OCCNs, we restrict our attention to them in an attempt to develop a general method for constructing OCCNs on an arbitrary number of nodes.

4.3.2 Gunther-Hartnell Construction

As mentioned in Section 2.6, Gunther and Hartnell describe two similar network topologies in [27, 30]. These topologies are built by connecting cliques of order k.

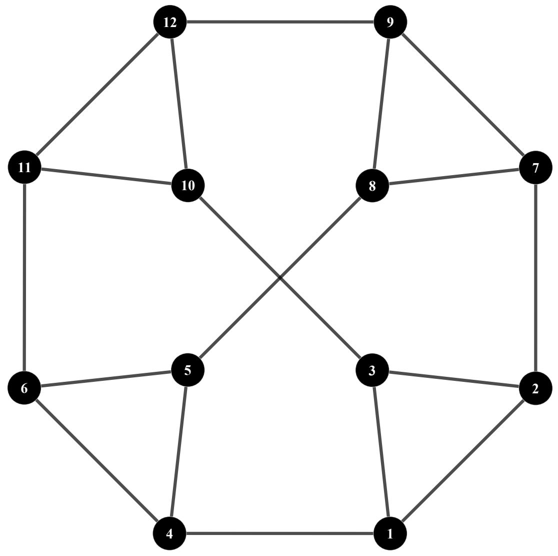


Figure 4.3: Gunther-Hartnell construction, Cl_3.

'Clique' graphs, Cl_k are constructed with $k+1$ cliques in which each of the k nodes within a given clique is also connected to a node within a different, unique clique. In the 'courier' graphs, Co_k, k cliques are connected in the same way with the remaining node connected to a separate node that is not a member of a clique. Both Cl_k and Co_k graphs are k-connected and k-neighbor connected and have an order $n = k^2 + k$.

Theorem 4.3.1. Graphs generated by the Gunther-Hartnell construction have an optimal subversion impedance.

Proof. Deleting any closed neighborhood will remove an entire clique plus one vertex in another clique. Thus,

$$\begin{aligned}\gamma^*(Cl_k) &= \frac{|H^*(Cl_k)|}{|Cl_k|} \times \frac{\kappa(H^*(Cl_k))}{\kappa(Cl_k)} \\ &= \frac{n-(k+1)}{n} \times \frac{k-1}{k} \quad = \quad \Gamma(n) \quad .\end{aligned}$$

and, from Equation 4.12

$$k^2 - k + 2 \leq k^2 + k \leq k^2 + k + 1 \quad .$$

Thus, topologies constructed using the Gunther-Hartnell method have optimal subversion impedance. $\square$

4.4 Conclusions

In this section, we have presented an approach for measuring the suitability of topologies for use in CCNs. We refer to this measure as subversion impedance. The higher the subversion impedance of a topology, the better it is at balancing secrecy and resilience. We have found that the family of $(k;5)$-*cages* are optimal, but there are only a limited number of these graphs that are known, and no algorithm is known that will construct optimal graphs of arbitrary order. We also demonstrated that topologies built using the Gunther-Hartnell construction also have optimal subversion impedance. Though more robust than cage construction, the Gunther-Hartnell construction will not create topologies of arbitrary order. In Section 5, we present constructions for each of these graph families that have near-optimal subversion impedance for networks of arbitrary order.

5. DETERMINISTIC TOPOLOGY ANALYSIS FOR CCNs

Covert communication networks must be connected in order to enable communications between any pair of nodes. Given our particular threat model, we want networks that are as sparsely connected as possible in order to minimize network promiscuity but resilient against disconnection even after the removal of one or more closed neighborhoods. As discussed in Section 3.2.1, low network promiscuity can be achieved through a sparsely connected topology such as that of a tree. A tree topology can become partitioned after a single subversion but will often minimize the number of nodes compromised from a single subversion. On the other hand, a more densely connected graph is more resilient but, thus, will usually have larger numbers of nodes directly affected by the subversion of a single node.

5.1 Resilience versus Survivability

Gunther-Hartnell topologies, described in [30] and Section 4.3.2, are resilient to k subversions, but each subversion removes $k + 1$ nodes from the network. For this reason, Gunther and Hartnell refer to these topologies as being k-neighbor-connected. Removing $k + 1$ neighborhoods eliminates all nodes within the topology. This topology construction offers optimal global subversion impedance when the graph contains $k(k+1)$ nodes. Other topology constructions, on the same number of nodes and similar number of edges, might become disconnected after the removal of fewer closed neighborhoods but require the removal of more closed neighborhoods in order to deplete the network. Based on the priorities of the organization relying on the CCN, the organization must determine whether it is better to maintain a topology that remains connected through multiple subversions or becomes disconnected at some point in order to provide a greater degree of node survivability.

From the adversary's perspective, the problem of bringing down all the nodes in a CCN is related to the problem of constructing a dominating set of a graph. For a given graph, $G = (V, E)$, a *dominating* set is a set of nodes $W \subseteq V$ such that every node in the graph G is a neighbor of at least one element of W [36]. The *minimum dominating set* (MDS) problem, a classical problem within computer science and graph theory, is to find a minimum such W for a given graph. Thus, in order to collect the network addresses of all participants within the CCN, the adversary would need to subvert at least W nodes. Even assuming that the adversary knows the network topology, finding a minimum dominating set is NP-hard in general. In the following, we will focus on networks with large MDSs.

5.2 Worst Case Subversion versus Uniformly Probable Subversion

As discussed in Section 4, the *a priori* subversion probability distribution is difficult to quantify. It can be simplified to either the worst-case or the uniform case. Analyzing both cases is important in assessing CCN topologies.

We do not wish to allow topologies that protect some nodes by placing others at risk. No one will want to participate within the CCN if there is a chance that they will be sacrificed to the adversary in order to protect the other nodes. Instead, we would prefer topologies in which most nodes have a similar local subversion impedance and the global subversion impedance is not significantly lower than the average local subversion impedance.

For a given graph G, the global subversion impedance $\gamma^*(G)$ gives us the worst case measure. We make the assumption that the adversary had sufficient knowledge to subvert the node that would do the greatest damage to the network. However, in practical terms, this will rarely be the case. A uniform distribution provides a differing *a priori* probability distribution for node subversion—one in which every node in the network has the same chance of being subverted. Thus, as a different measure for the topology suitability in CCNs, we examine cases in which the *a priori* subversion probability is equal for all nodes. Thus, the risk to the network is measured as the *average local subversion impedance.*

5.3 Average Local Subversion Impedance

We modify the global subversion impedance measure so that it is calculated as the average local subversion impedance instead of the worst-case local subversion impedance. By extension, we also specify the *average secrecy measure* and the *average resilience measure.*

Definition 5.3.1. *The* average (local) subversion impedance *on graph G is:*

$$\langle\gamma(G)\rangle = \frac{1}{|G|}\sum_{v\in V}\gamma(G,v) \quad . \tag{5.1}$$

Definition 5.3.2. *The* **average secrecy measure** *on a given graph G is:*

$$\begin{aligned}\langle S(G)\rangle &= \frac{1}{|G|}\sum_{v\in V}S(G,v)\\ &= \frac{|G| - \langle d(G)\rangle - 1}{|G|} \quad ,\end{aligned} \tag{5.2}$$

where $\langle d(G)\rangle$ is the average node degree within the network.

Definition 5.3.3. *The* **average resilience measure** *on a given graph G is:*

$$\langle K(G)\rangle = \frac{1}{|G|}\sum_{v\in V}\frac{\kappa(H(G,v))}{\kappa(G)} \quad . \tag{5.3}$$

Each of these measures give us insight into the usefulness of topologies for use in a CCN. Given that the average degree is easily calculated for many types of deterministic topologies, the average secrecy measure $\langle S(G)\rangle$ is often easily determine. However, since vertex connectivity is a global property of a graph and is often difficult to easily determine for topologies with an arbitrary number of nodes, $\langle K(G)\rangle$, in turn, is not easily reducible in the same manner as $\langle S(G)\rangle$. The complexity of calculating $\gamma^*(G)$ is dominated by the complexity of calculating the vertex connectivity of G.

Given $\langle S(G)\rangle$ and $\langle K(G)\rangle$, we want to clarify that,

$$\langle \gamma(G)\rangle \neq \langle S(G)\rangle \times \langle K(G)\rangle \quad ,$$

unless either $S(G, v)$ or $K(G, v)$ are constant for all $v \in V$ (for example, in symmetric topologies).

With both the measure for global subversion impedance and the measure for average local subversion impedance, we now examine various P2P network topologies for suitability of use within covert communications networks.

5.4 An Analysis of Common Network Topologies for Use in CCNs

We now examine some common deterministic topologies used in overlay networks. We use our measures for subversion impedance to assess the suitability of each topology for use in a CCN.

5.4.1 Paths

A *path*, P_n, topology consists of a linear chain of n nodes. Except the two nodes on each end, which are attached to only one adjacent node, all nodes are attached to two adjacent nodes. As new nodes join the network, they connect to the node at either end of the topology. Figure 5.1 shows an example of a path topology on five nodes.

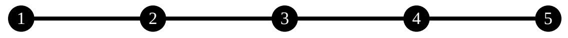


Figure 5.1: Path topology on 5 nodes, P_5

When n is large, a path topology does tend to have both a relatively high worst-case secrecy measure and average secrecy measure:

$$S(P_n, v^*) = \frac{|P_n| - 3}{|P_n|} \quad , \tag{5.4}$$

and

$$\langle S(P_n) \rangle = \frac{(|P_n| - 2)(|P_n| - 1)}{|P_n|^2} \quad . \tag{5.5}$$

However, the worst-case resilience measure is $K(P_n, v^*) = 0$, and the average resilience measure is very low. If a node at either end of the path or adjacent to the end node is subverted, then a portion of the graph survives and remains connected. Otherwise, the graph becomes disconnected. This occurs regardless of the length of the path, but the length of the path does affect the average resilience,

$$\langle K(P_n) \rangle = \frac{4}{|P_n|} \quad , \tag{5.6}$$

as long as $n \geq 4$ and continually grows smaller as n increases.

For a path topology with any number of nodes, the global subversion impedance, $\gamma^*(P_n) = 0$. The average local subversion impedance for a path topology with $n \geq 3$ is:

$$\langle \gamma(P_n) \rangle = \frac{4n-10}{n^2} \quad . \tag{5.7}$$

When $n \leq 2$, $\langle \gamma(P_n) \rangle = 0$.

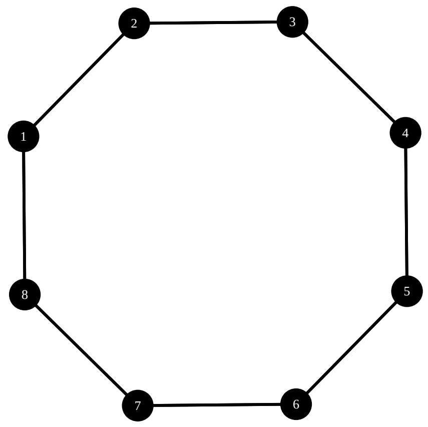


Figure 5.2: Cycle topology on 8 nodes, C_8

5.4.2 Cycles

A *Cycle*, C_n, is a graph on n nodes formed when the two ends of a path topology are also connected. Figure 5.2 shows an example of a cycle topology on 8 nodes. We observe that

$$\delta(C_n) = \Delta(C_n) = E[d(C_n)] = 2 \quad . \tag{5.8}$$

However, given the symmetry of a cycle, for all cycles with $n \geq 3$, for all $v \in V$,

$$S(C_n, v) = \langle S(C_n) \rangle = \frac{n-3}{n} \quad , \tag{5.9}$$

$$K(C_n, v) = \langle K(C_n) \rangle = \frac{1}{2} \quad , \tag{5.10}$$

and, thus, by the symmetric nature of cycles,

$$\gamma^*(C_n) = \langle \gamma(C_n) \rangle = \langle S(C_n) \rangle \times \langle K(C_n) \rangle = \frac{n-3}{2n} \quad . \tag{5.11}$$

In order to grow a cycle topology, new nodes are inserted between two existing nodes. If node x is to be inserted between two adjacent nodes, i and j, then the edge between i and j is removed and two new edges are added between i and x and x and j. This is problematic in a CCN in that the network promiscuity of nodes constantly increases as the network grows, but the connectivity of the topology remains $\kappa(G) = 2$.

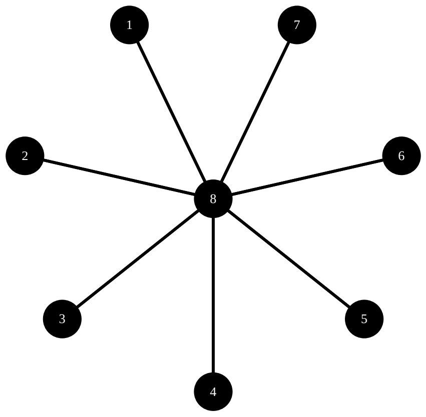


Figure 5.3: Star topology on 8 nodes, S_8.

5.4.3 Stars

A *star* topology, S_n, is one consisting of a single central node adjacent to all other nodes. All other nodes are only connected to the central node. Figure 5.3 shows an example of this topology. New nodes join the network by connecting to the central node. A source node is never more than two hops away from a destination node.

Given our threat model, if the central node becomes subverted, then all other nodes within the network become compromised. If an outer node becomes subverted, then the central node becomes compromised. In the first case, no node survives, $S(S_n, v^*) = 0$ and $K(S_n, v^*) = 0$. In the second, most nodes survive, so

$$\langle S(S_n) \rangle = \frac{(n-1)(n-2)}{n} \quad , \tag{5.12}$$

but the network becomes disconnected, $\langle K(S_n, v) \rangle = 0$. Thus, in either case,

$$\gamma^*(S_n) = \langle \gamma(S_n) \rangle = 0 \quad . \tag{5.13}$$

We can see in the star topology that most of the risk seems to be localized in the central node. It has a very high network promiscuity while all other nodes have a very low network promiscuity. Thus, if there is a uniform probability of subversion, then the central node will always be compromised, insuring the survivability of all other nodes, but at the expense of resilience.

5.4.4 Cliques

A *clique*, K_n, is a fully-connected graph; that is, a topology in which every node is connected to every other node. Figure 5.4 shows an example of a clique. In this topology, a joining node connects directly to all other nodes within the network, and the shortest path between any two nodes is one hop. The network promiscuity of

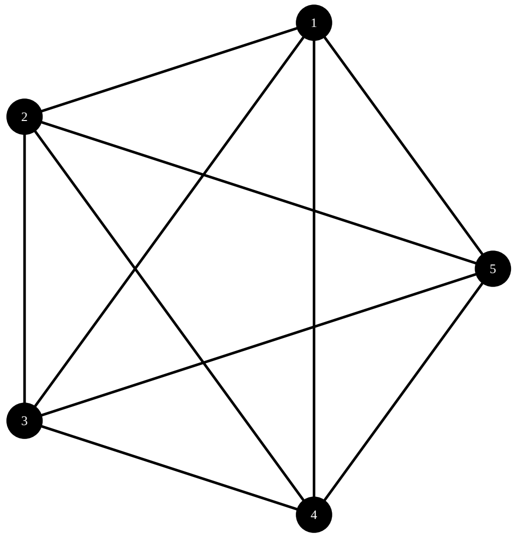


Figure 5.4: Clique topology on 5 nodes, K_5.

any node within the network is sufficient, however, such that a single subversion of any node compromises the entire network. Thus,

$$\gamma^*(K_n) = \langle \gamma(K_n) \rangle = \langle S(K_n) \rangle = \langle K(K_n) \rangle = 0 \quad . \tag{5.14}$$

In traditional settings, a clique is the most resilient network topology. However, given our threat model, it serves as a very poor choice for use in a CCN.

5.4.5 Fifth-Column Graphs

Fifth-column graphs, F_ℓ, were presented by Gunther and Hartnell [30] as a topology for an underground resistance movement that minimizes the damage done by b subversions, thus maximizing the number of surviving nodes. An example of a fifth-column graph is shown in Figure 5.5. The graphs are constructed by connecting ℓ paths of 5 nodes in a series (a fifth-column), with the third node in each path also connected along a orthogonal path. They demonstrated that fifth-column graphs were optimal for b subversions when the order of the network was within the range

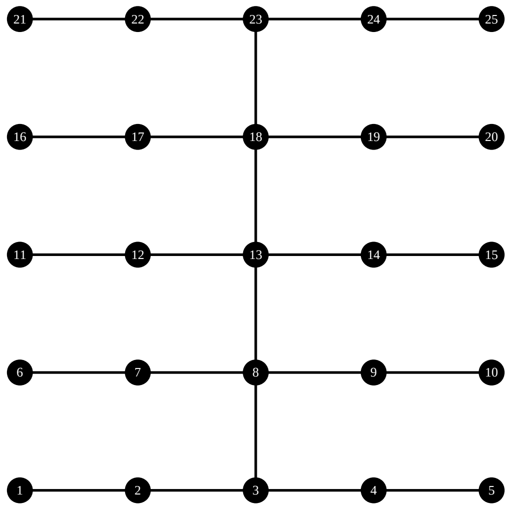


Figure 5.5: Fifth-column network on 25 nodes, F_5.

of $\frac{10}{3}b \leq n \leq 5b - 4$.

In our examination, however, fifth-column graphs are easily disconnected. Thus, the global subversion impedance of such graphs are $\gamma^*(F_\ell) = 0$. These graphs are slightly more resistant to a random subversion. Since $|F_\ell| = 5\ell$, the average secrecy is

$$\begin{aligned} \langle S(F_\ell) \rangle &= \frac{5\ell - \left[\frac{10\ell-2}{5\ell}\right] - 1}{5\ell} \\ &= \frac{25\ell^2 - 15\ell + 2}{25\ell^2} \quad . \end{aligned} \tag{5.15}$$

The survivor graph remains connected whenever one of the two outside nodes of each fifth-column is subverted. Otherwise, the survivor graph is disconnected. When $\ell \geq 2$, this results in an average resilience of

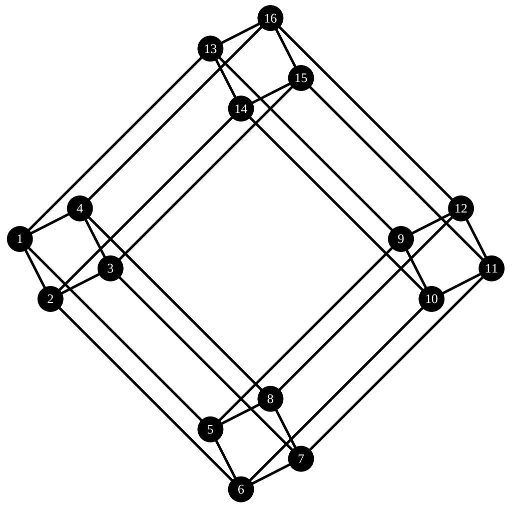


Figure 5.6: A 4-Hypercube or Tesseract.

$$\langle K(F_\ell) \rangle = \frac{2}{5} \quad . \tag{5.16}$$

Finally, the average subversion impedance for F_ℓ with $\ell \geq 2$ can be calculated as

$$\langle \gamma(F_\ell) \rangle = \frac{10\ell - 4}{25\ell} \quad . \tag{5.17}$$

When $\ell = 1$, we have a single path of five nodes and the discussion with regards to paths, above, applies.

5.4.6 Hypercubes

A d-dimensional *hypercube* (or d-cube), H_d, is a network with $|H_d| = 2^d$ nodes such that Node x has a direct connection to Node y if and only if the binary representations of x and y differ in exactly one bit [41]. Figure 5.6 is an example of a hypercube with $d = 4$ known as a tesseract. Since complete hypercubes are symmetric, the average secrecy is the same as the worst-case secrecy:

$$\langle S(H_d) \rangle = S(H_d, v^*) = \frac{2^d - d - 1}{2^d} \quad , \tag{5.18}$$

when $d \geq 1$, and the average resilience is also the same as the worst-case resilience:

$$\langle K(H_d) \rangle = K(H_d, v^*) = \frac{d-2}{d} \quad . \tag{5.19}$$

Thus, the global subversion impedance is the same as the average local subversion impedance, i.e., the product of the average secrecy and average resilience:

$$\gamma^*(H_d) = \langle \gamma(H_d) \rangle = \langle S(H_d) \rangle \times \langle K(H_d) \rangle \quad . \tag{5.20}$$

Of the topology constructions examined in this section, hypercubes provide topologies that are best suited for use in CCNs. Though hypercubes have relatively high average local subversion impedance and global subversion impedance, in general they are not OCCNs. Additionally, the measures in Equation 5.20 hold for "complete" hypercubes; that is, hypercubes with 2^d nodes. We need topologies that maintain relatively high subversion impedance regardless of the number of nodes in the network. Thus, in the following sections, we describe the difficulty of extending regular topologies.

5.5 The Modified Robertson Construction

In Section 4, we discussed two families of topologies that were proven, in certain cases, to be OCCNs. These two graph families were: (1) the girth-5 cages; and (2) the Gunther-Hartnell topologies. The problem with both of these graph families is that they were optimal only for graphs of particular orders. CCNs need to have high subversion impedance regardless of the number of nodes. We now describe two approaches that allows us to grow CCN topologies in such a way as to maintain near-

```
Algorithm Robertson construction :

Input: Set of 50 nodes.
Output: A 7-connected, 7-regular graph G with girth(G) $\geq 5$.

Step 1: Partition the nodes into 10 sets of 5 nodes each.
Step 2: Connect the nodes in each of the first 5 sets to create 5 pentagrams
        $P_1, \ldots P_5$.
Step 3: Connect the nodes in each of the remaining 5 sets to create 5 pentagons
        $Q_1, \ldots, Q_5$.
Step 4: Label each node in each pentagram and pentagon from 1 to 5.
Step 5: Connect each node $k$, $(1 \leq k \leq p)$, of Pentagram $P_i$ with node $k+ij$ $(mod$
        $5)$ of Pentagon $Q_j$.
```

Figure 5.7: Robertson construction of the Hoffman-Singleton graph.

optimal subversion impedance on topologies with an arbitrary number of nodes. We first describe an approach based on girth-5 cages and then an approach based on Gunther-Hartnell topologies.

5.5.1 Robertson Construction

We showed in Section 4.3.1 that the known girth-5 cage graphs have optimal subversion impedance. The establishment of girth-5 cage topologies has two significant limitations. First, no general method is known for generating cage graphs. Second, only a few girth-5 cages are known. For example, the $(3;5)$-*cage* has 10 nodes, the $(4;5)$-*cage* has 19 nodes, the $(5;5)$-*cage* has 30 nodes, the $(6;5)$-*cage*

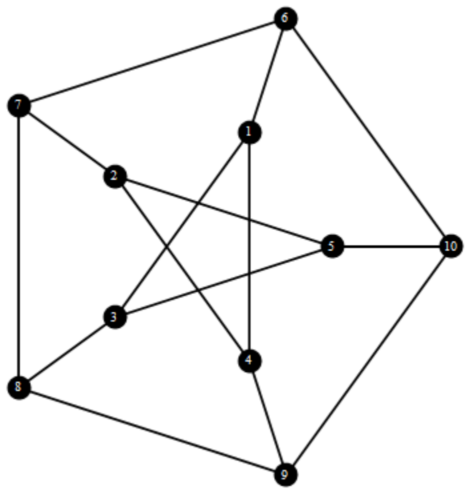


Figure 5.8: $(3;5)$-*cage* - The Peterson graph

has 40 nodes, and the largest known girth-5 cage is the $(7;5)$-*cage* with 50 nodes [6, 55, 68]. For any number of nodes in-between, there exists no girth-5 cage, and the subversion impedance of graphs is significantly lower than optimal. A method is therefore needed that (a) allows for large girth-5 graphs with high subversion impedance, (b) allows for graphs with arbitrary number of nodes, and (c) allows for graphs to grow without requiring nodes to reconnect to new nodes and so increase their network promiscuity. In the following, we describe a construction technique, based on Robertson's technique to construct such graphs [55].

Robertson [19, 55, 68] constructs girth-5 cages by connecting pentagons and pentagrams. Examining the *Petersen Graph* in Figure 5.8, we easily see one pentagon connected to one pentagram. The construction method extends this idea to connecting 5 pentagrams (P_0, P_1, P_2, P_3, P_4) to 5 pentagons (Q_0, Q_1, Q_2, Q_3, Q_4) in the so-called Hoffman-Singleton Graph [6, 31] construction, described in Figure 5.7. Figure 5.9 shows connections for a single node (node 3 of P_2).

We implemented the construction as an algorithm to build graphs of various sizes

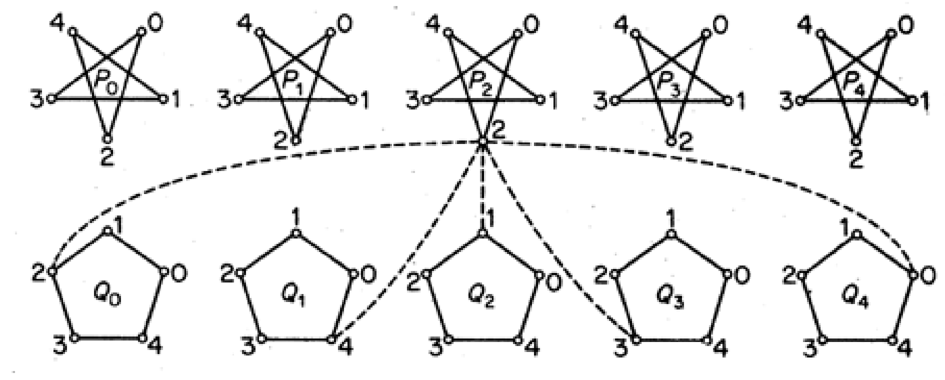


Figure 5.9: Robertson's Method for constructing the Hoffman-Singleton graph [6].

($n \leq 50$). Limiting the construction to 3 pentagrams and 3 pentagons gives us the *Robertson-Wegner Graph* which is the [63, 68] and 4 of each cycle type produces the *Foster Cage* [46, 67, 68]. For the case of 2 pentagrams and 2 pentagons, the algorithm produces a *4-regular* graph on 20 nodes with *girth* = 5. Though this graph is not the $(4; 5)$-*cage* [54], it is an optimal covert communications network topology on 20 nodes, just as the actual $(4; 5)$-*cage* is an optimal covert communications network topology on 19 nodes.

In the constructions above, the size of the base cycle is 5: two types of *5-cycles* (pentagrams and pentagons) construct our graph. In the following, we extend the *Robertson construction* using a base cycle of size p, where p is any prime number greater than or equal to 5.

5.5.2 Modified Robertson Construction

Robertson's construction can be generalized to generate near-optimal covert communications network graphs for prime base cycle sizes. Figure 5.10 describes the construction algorithm.

With this algorithm, notice that we connect each node in a p-gram to each node in a p-gon by a fixed offset, ij (i.e., for a given p-gram, P_i, and a given p-gon, Q_j, as

Algorithm **Modified Robertson construction :**

Input: Cycle size $p \geq 5$, where p is prime; integer q, where $1 \leq q \leq p$; set of $2pq$ nodes.

Output: Near-optimal covert communications network topology of size $2pq$.

Step 1: Connect pq nodes into q cycles $Q_1, \ldots, Q_q$ of order p each (p-gons). Label each node in p-gon Q_i from 1 to p.

Step 2: Connect the remaining pq nodes into q p-grams $P_1, \ldots, P_q$ as follows:

- **Step 2.1: Label each node in p-gram P_j from 1 to p.**
- **Step 2.2: In every p-gram P_j, connect every node k, $(1 \leq k \leq p)$, with node $k + 2(mod\ p)$.**

Step 3: Connect each p-gram P_i to each p-gon Q_j by connecting every node k, $(1 \leq k \leq p)$, on P_i to node $k + ij\ (mod\ p)$ on p-gon Q_j.

Figure 5.10: Modified Robertson construction.

we iterate through each node, k, the offset $ij\ (mod\ 5)$ does not change). Thus, the graph generated from the construction algorithm is easily represented by an *offset matrix.*

Definition 5.5.1. *We define the* **offset matrix**, *h, as the $m \times n$ matrix that contains the set of values such that each element a_{ij} is the fixed offset used to connect the p-gon Q_i to the p-gram P_j.*

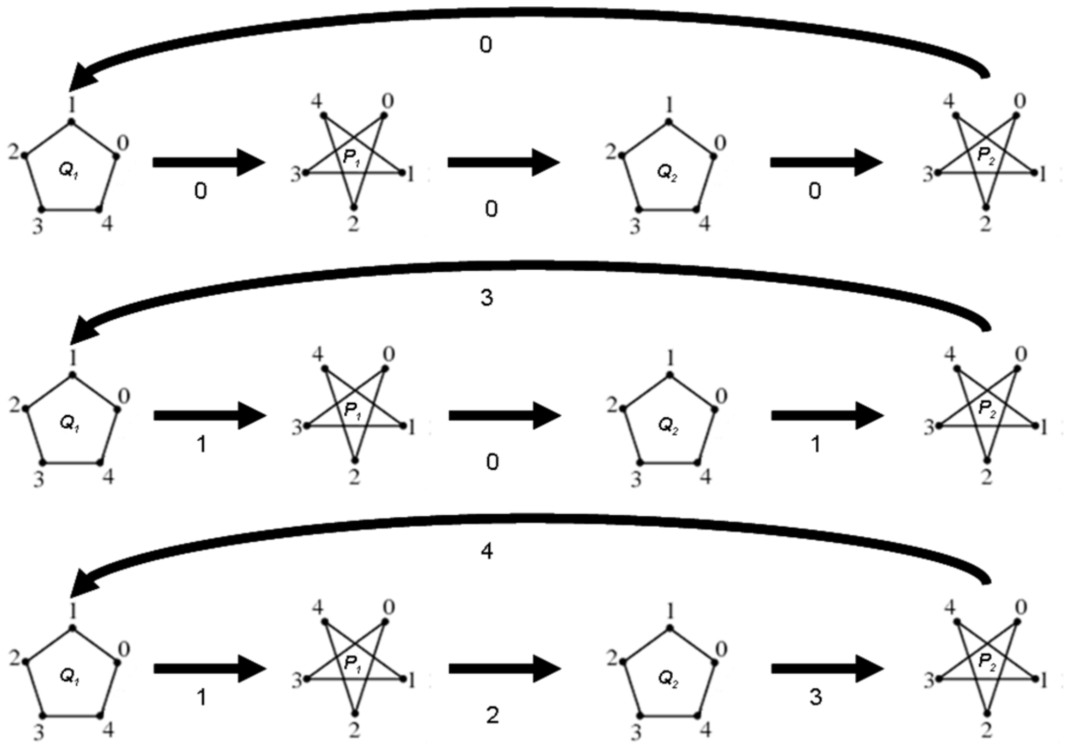


Figure 5.11: Ways to NOT connect pentagons and pentagrams.

$$h = \begin{pmatrix} a_{0,0} & \cdots & a_{m,0} \\ \vdots & \ddots & \vdots \\ a_{0,n} & \cdots & a_{m,n} \end{pmatrix}.$$

Lemma 5.5.1. An *offset matrix*, h will produce a graph G, such that $girth(G) = 5$ if, and only if, for all sets of 4 rectilinear values in the matrix

$$h = \begin{pmatrix} & \vdots & & \vdots & \\ \cdots & a_{i_1 j_1} & \cdots & a_{i_2 j_1} & \cdots \\ & \vdots & & \vdots & \\ \cdots & a_{i_1 j_2} & \cdots & a_{i_2 j_2} & \cdots \\ & \vdots & & \vdots & \end{pmatrix}$$

where $i_1 \neq i_2$ and $j_1 \neq j_2$,

$$[a_{i_1 j_1} + a_{i_2 j_2}]_p \neq [a_{i_1 j_2} + a_{i_2 j_1}]_p \quad .$$

Proof. By construction, we are connecting nodes in a p-gram to nodes in a p-gon and vice-versa. In order to construct a graph of girth 4, the algorithm would need to construct at least one cycle of length 4. In order for such a cycle to exist, there would have to exist a set of nodes v_A and v_C on two different p-gons and v_B and v_D on two different p-grams such that v_A would connect to v_B, v_B to v_C, v_C to v_D, and v_D back to v_A.

This occurs only when the offsets sum to a multiple of the size of the base cycle. Figure 5.11 shows the case for $p = 5$. Notice that the offsets are directional. In the notation of our *offset matrix*, each entry in h is from the i^{th} *p-gram* to the j^{th} *p-gon*. Thus,

$$a_{i_1 j_1} - a_{i_1 j_2} + a_{i_2 j_1} - a_{i_2 j_2} \not\equiv 0 \textit{ (mod p)} \quad ,$$

which is equivalent to

$$[a_{i_1 j_1} + a_{i_2 j_2}]_p \neq [a_{i_1 j_2} + a_{i_2 j_1}]_p \quad .$$

Thus, completing the proof. $\square$

Theorem 5.5.1. An *offset matrix*, h with entries $a_{i,j} = ij\ (mod\ p)$ will produce a graph G with $girth(G) = 5$ if, and only if, (1) the matrix is no larger than $p \times p$; and (2) p is prime.

Proof. Let $[a_{i_1 j_1} + a_{i_2 j_2}]_p \neq [a_{i_1 j_2} + a_{i_2 j_1}]_p$. Then,

$$\begin{aligned}
[a_{i_1 j_1} + a_{i_2 j_2}]_p &\neq [a_{i_1 j_2} + a_{i_2 j_1}]_p \\
[i_1 \cdot j_1]_p + [i_2 \cdot j_2]_p &\neq [i_1 \cdot j_2]_p + [i_2 \cdot j_1]_p
\end{aligned}$$

for $i_1 \neq i_2$ and $j_1 \neq j_2$. And,

$$\begin{aligned}
[i_1 j_1]_p + [i_2 j_2]_p &\neq [i_1 j_2]_p + [i_2 j_1]_p \\
[i_1 j_1 + i_2 j_2]_p &\neq [i_1 j_2 + i_2 j_1]_p \\
[i_1 j_1 + i_2 j_2]_p - [i_1 j_2 + i_2 j_1]_p &\neq 0 \\
[(ij - in) + (mn - mj)]_p &\neq 0 \\
[i_1(j_1 - j_2) + i_2(j_2 - j_1)]_p &\neq 0 \\
[(j_1 - j_2)(i_1 - i_2)]_p &\neq 0
\end{aligned}$$

If our *offset matrix* is $p \times p$ or smaller, then $0 \leq i, j < p$ and $-p < (i_1 - i_2), (j_1 - j_2) < p$. Since $i_1 \neq i_2$ and $j_1 \neq j_2$ then $i_1 - i_2 \neq 0$ and $j_1 - j_2 \neq 0$. If p is prime, then all values of $(i_1 - i_2)$ and $(j_1 - j_2)$ will be *co-prime* with p. Thus, for no values of i_1, i_2, j_1 and j_2 is $[(j_1 - j_2)(i_1 - i_2)]_p \neq 0$. On the other hand, if p is not prime, then there is

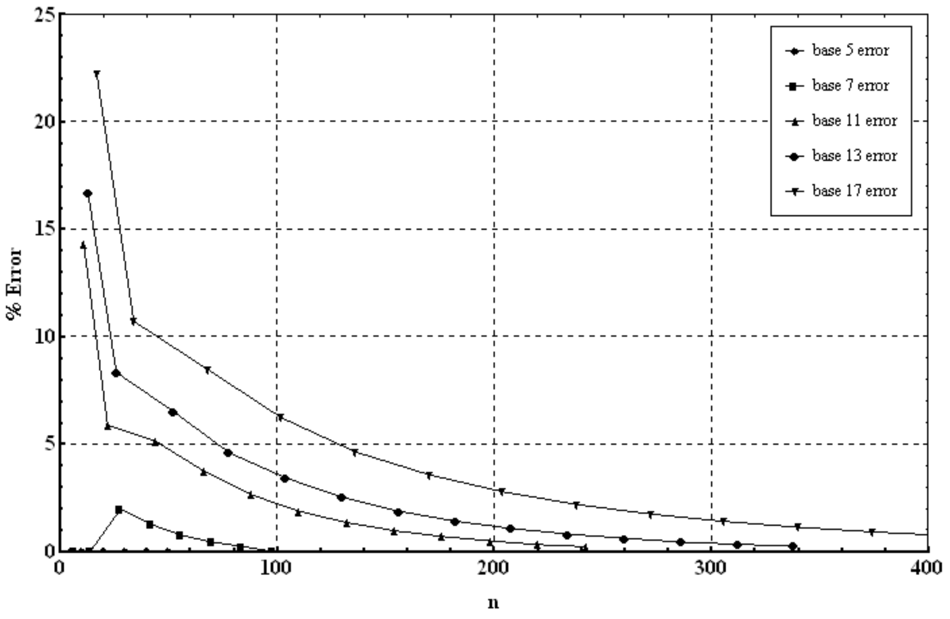


Figure 5.12: Percent error between $\gamma^*(G)$ and the upper bound on graphs constructed using the Modified Robertson construction for various base size p.

some i, j such that $i \times j = p$ and the *offset matrix* does not produce a *girth 5* graph (the top row and left column entries are always 0).

Finally, if the *offset matrix* is larger than $p \times p$, then even if p is not divisible by i_1, there exists j_1 and j_2 such that $i_1 j_1 \ (mod\ 5) = i_1 j_2 \ (mod\ 5)$ and the *offset matrix* does not produce a *girth 5* graph (set $i_2 = 0$). □

Given the $p \times p$ size restriction to an *offset matrix* from Theorem 5.5.1, the *Modified Robertson construction* algorithm limits the order of the graphs we can construct to $n = 2p^2$.

5.5.3 Analysis of the Modified Robertson Construction

We have seen that using the Robertson construction to generate graphs with $p = 5$ produces optimal covert communications network topologies for $n = 10, 20, 30, 40,$ and 50. However, in order to build graphs of larger order, by Theorem 5.5.1, we must increase p. We can easily see, by the same logic we used to show that $(k; g)$-*cages* were not optimal for $g > 5$, that as we increase p, we increase the order of the graph for a given k. Thus, for $p > 5$, most of the graphs constructed by the Modified Robertson construction may not be optimal covert communications network topologies. For example, for $p = 13$, the largest possible graph G has $2p^2 = 338$ nodes and is $k = 15$-*regular*. Thus,

$$\gamma^*(G) = \frac{2254}{2535} < \frac{5423}{6084} = \text{upper bound of } \gamma^*(338) \quad ,$$

which is at least 99.75% optimal. (Note: At the risk of abuse of terminology, we use the term "optimal" to denote both a graph with an optimal subversion impedance and the relative measure of the graph compared to the optimal value, as in "level of optimality".) However, for the same $p = 13$, the graph constructed on $n = 26$ nodes evaluates at

$$\gamma^*(G) = \frac{22}{39} < \frac{8}{13} = \text{upper bound of } \gamma^*(26)$$

and is only at least 90% optimal. Figure 5.12 plots the error in optimality of graphs of increasing order constructed using various prime values for p. In summary, we make two observations about the effectiveness of the Modified Robertson construction. First, the optimality of the constructed graphs increases with increasing graph order for a given choice of p. Second, the optimality generally decreases for larger selections of p. To our knowledge, the Modified Robertson construction is the first scalable algorithm that constructs graphs of the same order of node degrees (i.e., proportional to the square root of the number of nodes) as optimal graphs.

5.6 Moving Towards Dynamic Construction

Up to this point, our construction algorithms have been static; for a given number of nodes n, the objective was to construct an optimal or near-optimal graph. The Modified Robertson construction could potentially provide a mechanism for a more dynamic approach to graph construction. In dynamic construction, we are looking to "grow" our graphs. This may happen in response to additional nodes joining the network. Thus, we might begin with a set of nodes, say $n \leq 50$, and construct a graph using a base cycle of $p = 5$. As we increase n up to 50, we can "grow" our network in such a way that we are assured that the graph is optimal for $n = 10k$ for $k = \{1, 2, 3, 4, 5\}$. However, once we fill the graph to its maximum order (by Theorem 5.5.1), we can no longer "grow" the graph using the base cycle of 5.

Limited by a maximum graph order for a given base cycle, to "grow" our graphs to an arbitrary size, we have three options:

- Option 1: *A priori* select a base cycle large enough to accommodate our anticipated maximum network size;
- Option 2: Grow to the maximum size relative to base size ($n = 2p^2$), then dissolve established connections and reconstruct the network with a larger base cycle; or
- Option 3: Set a given base cycle p and connectivity k and then grow the network linearly beyond the limit of $2p^2$ by using a different construction.

In the following, we will briefly discuss each of these options.

5.6.1 Option 1: Choose a Large Enough p

If we know ahead of time exactly what the order n of our network will be, then we can choose the smallest base cycle p such that $n \leq 2p^2$. This will insure that our constructed network is as close to G^n_{opt} as our algorithm can produce. Of course, as indicated earlier, if our estimated order proves to be too small, then our network will reach its maximum and we will need to resort to a different option. Furthermore, since the network may initially be significantly smaller than $2p^2$, it will have a significantly lower optimality than when it reaches its expected order. However, the error in optimality is bounded by Theorem 1 and Lemma 4 in Section 4.

5.6.2 Option 2: Reconstruct the Network When Necessary

Another option would be to maintain the smallest base cycle possible given the current order n. For example, a base cycle of $p = 5$ is used until the network reaches $n = 2p^2 = 50$. Then, existing connections (i.e. edges) are dissolved and nodes establish new connections with the next higher base cycle ($p = 7$). This allows for unlimited growth with a tightly bounded error in optimality. However, the overhead of having nodes reconnect in a new network is very high, and the risk of the network being discovered through elevated signaling and other protocol activity during network "restructuring" is significant. Also, each time a node builds a new neighborhood after each base cycle change, their network promiscuity increases. Thus, the probability of connecting to a subverted node increases, and a subverted node could compromise many more nodes than were in their initial neighborhood and further degrade membership concealment.

5.6.3 Option 3: Grow the Network Linearly

Alternatively, the base cycle size can be kept fixed, and the network can grow beyond the $2p^2$ limit by slightly altering the construction algorithm. Figure 5.13 presents an extension of the Modified Robertson construction for generating topologies of arbitrary size. It works by connecting multiple Modified Robertson construction topologies in a series.

Figure 5.14 graphs the subversion impedance of a linearly grown network with a base cycle $p = 5$ compared to the optimal subversion impedance. For $5 \leq n \leq 50$, there are the previously mentioned optimal covert communications network topologies. For other values, most have relatively high subversion impedance. A couple (i.e., $n = 51$) have a subversion impedance of 0. In this case, the majority of the nodes are well protected, but the new node is easily partitioned from the network given the worst-case subversion.

Figure 5.15 graphs the subversion impedance at the limit when $n \gg 100$. The subversion impedance becomes periodic over the range of $40k+50 \leq n \leq 40(k+1)+50$ with higher risk of partitioning for the newly joined nodes at $40k + 51$ and $40k + 52$.

5.7 The Extended Gunther-Hartnell Construction

Next, we try to extend our observations of the Gunther-Hartnell construction and see if we can generate near-optimal topologies from this approach.

Similar to the Extended Robertson construction, the Extended Gunther-Hartnell construction allows us to grow network topologies with an arbitrary number of nodes and relatively high subversion impedance. Figure 5.17 shows the subversion impedance for topologies with order $1 \leq n \leq 100$. We see that the subversion impedance goes to zero whenever a new clique is started. The risk of partitioning even in these cases is heavily weighted towards the new node. The new clique con-

```
Algorithm **Extended Robertson construction :**

Input:  Cycle size $p \geq 5$, where $p$ is prime; set of $n$ nodes.

Output:  Near-optimal covert communications network topology on $n$ nodes.

Step 1:  Construct the offset matrix $h$ with entries $a_{ij}$ as follows:

    Step 2.1:  Let $h$ be a $q \times r$ matrix where $q = \lceil \frac{n}{2p} \rceil$ and $r = \lfloor \frac{n}{2p} + 0.5 \rfloor$.
    Step 2.2:  Assign each entry of $h$ as $a_{ij} = -1$.
    Step 2.3:  Let $s = \lceil \frac{g1}{p-1} \rceil$.
    Step 2.4:  For each integer value of $0 \leq m < s$, $1 \leq i \leq p$ and $1 \leq i \leq p$:
        Step 2.4.1:  Let $x = i + (mp - m)$ and $y = j + (mp - m)$.
        Step 2.4.2:  If $x \leq q$ and $y \leq r$, then change the value of $a_{xy}$ as follows:
            If $[(x+m)(mod\ 2p)] > p$ or $[(y+m)(mod\ 2p)] > p$ then $a_{xy} = ij(mod\ p)$.
            Otherwise, $a_{xy} = (i-1)(j-1)(mod\ p)$.

Step 2:  Connect $pq$ nodes into $q$ cycles $Q_1, \ldots, Q_q$ of order $p$ each ($p$-gons).
    Label each node in $p$-gon $Q_i$ from 1 to $p$.

Step 3:  Connect the remaining nodes into $r$ $p$-grams $P_1, \ldots, P_r$ as follows:

    Step 3.1:  Label each node in $p$-gram $P_j$ from 1 to $p$.
    Step 3.2:  In every $p$-gram $P_j$, connect every node $k$, $(1 \leq k \leq p)$, with
        node $(k+2)(mod\ p)$.

Step 4:  If $a_{ij} \geq 0$, then connect each $p$-gram $P_i$ to each $p$-gon $Q_j$ by connecting
    every node $k$, $(1 \leq k \leq p)$, on $P_i$ to node $(k + a_{ij})(mod\ p)$ on $p$-gon $Q_j$.
```

Figure 5.13: Extended Robertson construction.

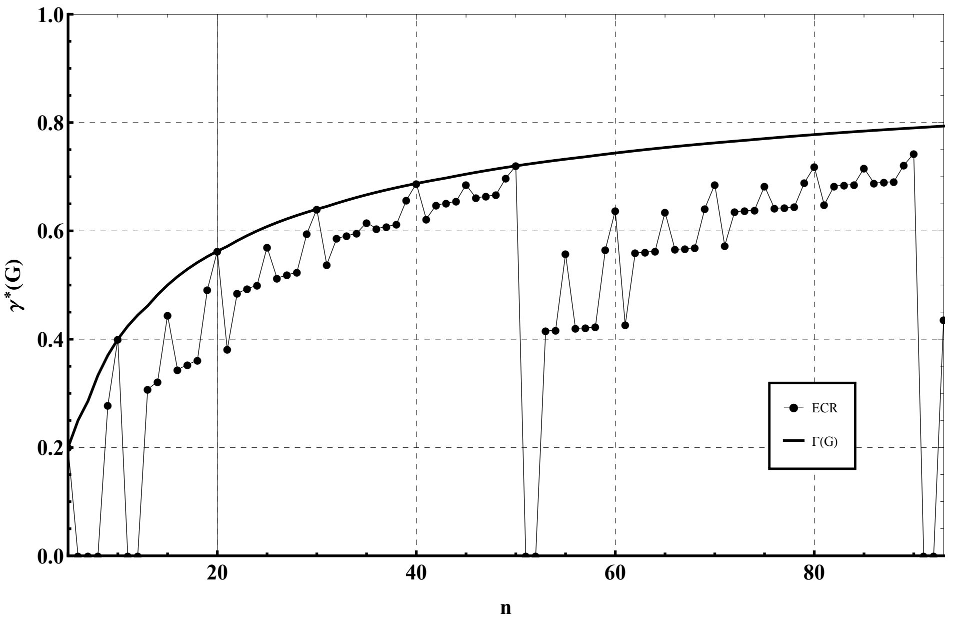


Figure 5.14: Subversion impedance for graphs of order $3 \leq n \leq 100$ using the Extended Robertson construction.

tains only one node with a single connection to a separate clique. If the separate clique is removed in accordance with our threat model, then the new node becomes partitioned from the rest of the network. If a second node is added to the clique, then the topology is, again, resilient to partitioning.

For graphs of arbitrary order with relatively few nodes, the Extended Gunther-Hartnell construction suffers from a higher risk of partitioning in that the subversion impedance is zero more often. However, as the number of nodes increase, new cliques are created less often. For a topology with $n > 625$, 50 new nodes can be added before starting a new clique. At this size, the subversion impedance is zero less often than if the Extended Robertson construction was used. The subversion impedance for this range is shown in Figure 5.18.

However, a considerable benefit of the Extended Gunther-Hartnell construction is that, regardless of the number of nodes in the topology, if $n = k(k+1)$ for

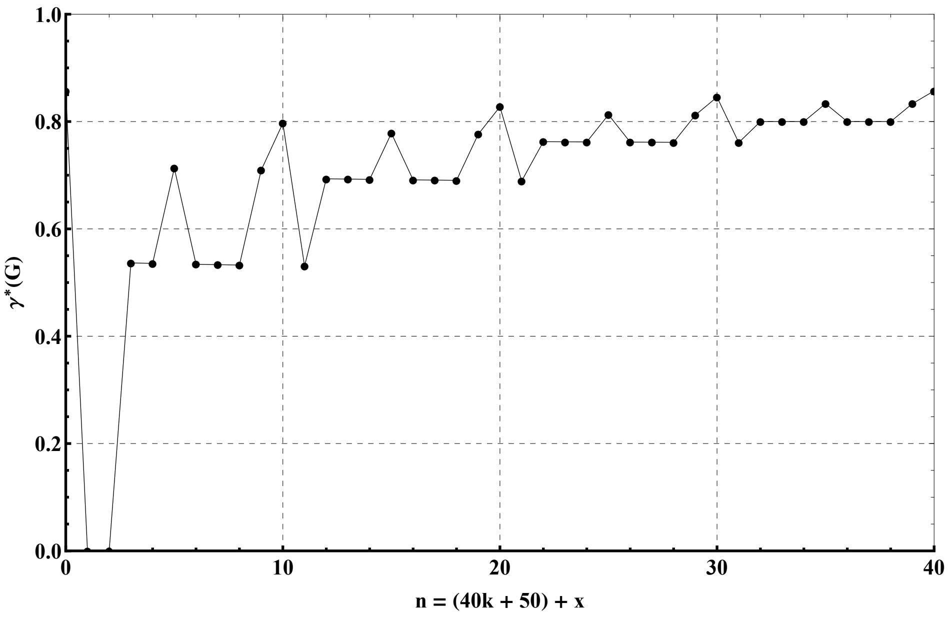


Figure 5.15: Subversion impedance for graphs of arbitrary order using the Extended Robertson construction (at the limit).

$k = \lceil(\sqrt{4n+1} - 1)/2\rceil$, then the topology is an optimal covert communications network topology. Discounting the cases where the subversion impedance is zero, the topologies built using the Extended Gunther-Hartnell construction are usually higher than those created by the Extended Robertson construction.

5.8 Conclusions

Covert communications networks provide traditional anonymity and privacy with the added requirements of membership concealment and resilience. Membership concealment is provided by restricting the network promiscuity of the network nodes; that is, the number of different nodes to which any given node can connect. A resilient CCN topology minimizes the number of other participants that have knowledge of a node's participation in the network while protecting the network against partitioning in the event of a subversion and removal of a closed neighborhood of nodes. The

Algorithm **Extended Gunther-Hartnell construction :**

Input: **Near-optimal covert communications network topology on $n-1$ nodes and a new node.**

Output: **Near-optimal covert communications network topology on n nodes.**

Step 1: **Calculate $k = \lceil(\sqrt{4n+1}-1)/2\rceil$.**

Step 2: **If $k(k-1) < n \leq k^2$, then add the new node to the first clique containing $k-1$ nodes.**

Step 3: **If $k^2 < n < k(k+1)$, then add the new node to the small clique. If there are only k cliques ($n = k^2+1$), then start a new clique**

Step 4: **Connect the new node to all other nodes within the same clique.**

Step 5: **Connect the new node to the appropriate node in the appropriate external clique, as follows:**

- **Step 5.1:** **If the node is the r^{th} node to join clique k and $r < k$, then the new node connects to node $k-1$ in clique k.**
- **Step 5.2:** **If the node is the r^{th} node to join clique k and $r = k$, then no new connections are added.**

Figure 5.16: Extended Gunther-Hartnell construction.

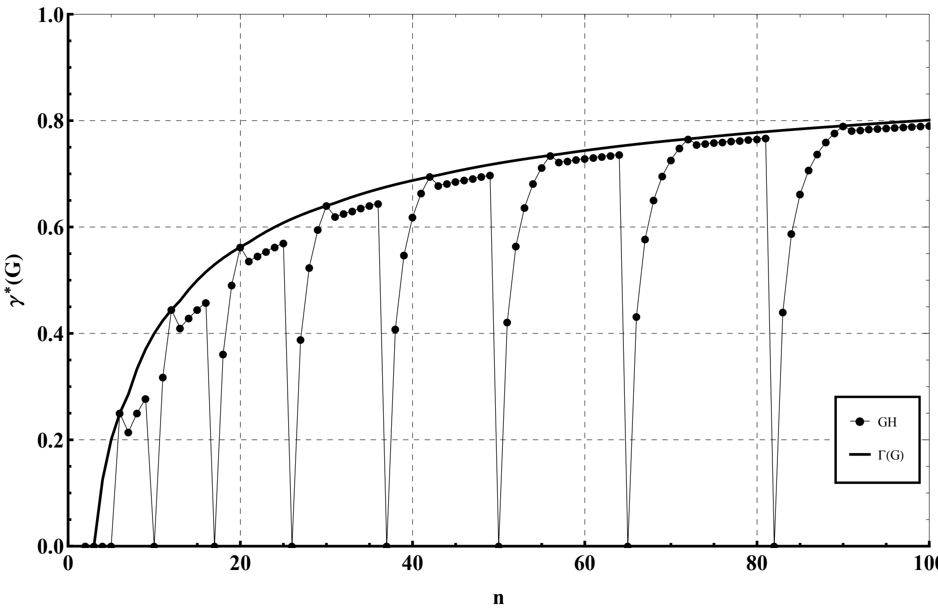


Figure 5.17: Subversion impedance for graphs of arbitrary order using the Gunther-Hartnell construction.

requirement to minimize network promiscuity and the need for network resilience against partitioning requires use to look for topologies that balance both.

We have presented an approach to maximizing subversion impedance by limiting the degree of connectivity within the network in order to minimize the necessary trust relationships and, thus, aid in preserving anonymity and membership concealment. A network with high subversion impedance will, with high probability, remain connected despite the removal of subverted nodes and their compromised neighbors. We have found that the family of $(k;5)$-*cages* are optimal, but there are only a limited number of these graphs that are known, and no algorithm is known that will construct optimal graphs of arbitrary order. However, there is a construction algorithm that will produce optimal graphs on $n = \{10, 20, 30, 40, 50\}$ nodes which can be generalized to producing resilient networks of arbitrary order. Our analysis shows the subversion impedance for these generated graphs and proves them to be resilient

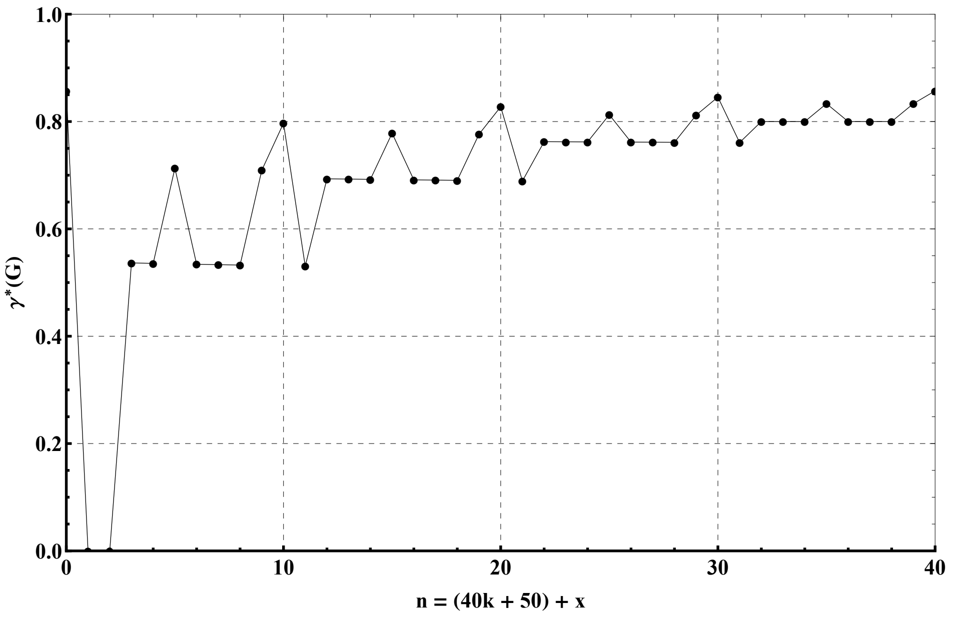


Figure 5.18: Subversion impedance for graphs of order for $k = 25$ using the Gunther-Hartnell construction.

against subversion. We also demonstrated that topologies built using the Gunther-Hartnell construction also have optimal subversion impedance. Though more robust than cage construction, the Gunther-Hartnell construction will not create topologies of arbitrary order. With the Extended Robertson construction and the Extended Guther-Hartnell construction techniques, we can grow topologies with low network promiscuity and high resilience against partitioning.

6. RANDOM TOPOLOGY ANALYSIS FOR CCNs

The topologies discussed in Section 5 all were deterministic, that is, any newly joining node would join the network at a well-defined location in the network according to a well-defined global ordering. In practice, such approaches can be rarely implemented in a CCN, mainly for two reasons. First, the join protocol would need to determine the global location of the new node in the network which in turn would require the network to determine (and possibly leak) information about the prospective neighbors of the new node. Second, the join protocol would need to be globally serialized. As a result, CCNs in practice would prevalently be non-deterministic, and would therefore have random topologies.

Examining subversion impedance in random topologies is somewhat trickier than in deterministic topologies, as there are many different graphs that can be generated for a given number of nodes.

Now, consider a random graph processes, $\mathfrak{G}$, in which a random graph evolves as the number of nodes, n, increases. We refer to the set of possible random graphs on n nodes as a *family* of random graphs denoted by $\mathfrak{G}_n$, where n is fixed. Now, we develop measures on families of random graphs to determine their suitability for use in CCNs.

As with the previous measures, we are interested in the risk incurred by the average participant when a node is subverted, uniformly, at random, as well as the case when the subverted node causes the most damage possible. Thus, we specify the *expected local subversion impedance* as a measure of the risk incurred by a random node and the *expected global subversion impedance* as the risk incurred by a node in the worst case for all graphs $G \in \mathfrak{G}_n$.

6.1 Expected Local Subversion Impedance

Recall that for deterministic topologies, we use the measures of secrecy, $S(G,v)$, and resilience, $K(G,v)$, for a given graph G and vertex v. Similarly, we use the measures of average local subversion impedance, $\langle\gamma(G)\rangle$, average secrecy, $\langle S(G)\rangle$, average resilience, $\langle K(G)\rangle$, and global subversion impedance, $\gamma^*(G)$, for a given graph, G.

Definition 6.1.1. *The* expected local subversion impedance*, $E[\gamma(G)]$, is the expected value of the local subversion impedance, $\langle\gamma(G)\rangle$, for all graphs $G \in \mathfrak{G}_n$;*

$$E[\gamma(G)] = \sum_{G\in\mathfrak{G}_n} \langle\gamma(G)\rangle Pr(G) \quad , \tag{6.1}$$

where $Pr(G)$ is the probability G occurs within $\mathfrak{G}_n$.

By extension, we can define both the *expected secrecy measure* and the *expected resilience measure.*

Definition 6.1.2. *The* expected secrecy *for all graphs $G \in \mathfrak{G}_n$ is:*

$$\begin{aligned} E[S(G,v)] &= \sum_{G\in\mathfrak{G}_n} \langle S(G,v)\rangle Pr(G) \\ &= \frac{n - E[d(v)] - 1}{n} \quad , \end{aligned} \tag{6.2}$$

where $E[d(v)]$ is the expected degree of node $v \in V$ within the network topology, $G(V,E) \in \mathfrak{G}_n$.

Definition 6.1.3. *The* expected resilience *for all graphs $G \in \mathfrak{G}_n$ is:*

$$\begin{aligned} E[K(G,v)] &= \sum_{G \in \mathfrak{G}_n} \langle K(G) \rangle Pr(G) \\ &= \frac{1}{n} \sum_{G \in \mathfrak{G}_n} \sum_{v \in V} \frac{\kappa(H(G,v))}{\kappa(G)} Pr(G) \end{aligned} \qquad (6.3)$$

We would like to be able to easily estimate the expected local subversion impedance on random graphs from $\mathfrak{G}_n$. Of course, since higher connectivity implies larger neighborhoods, $E[S(G,v)]$ and $E[K(G,v)]$ are correlated. Thus, we can expect $Cov[S(G,v), K(G,v)] \neq 0$. Thus, in order to calculate the expected local subversion impedance from the expected secrecy and the expected resilience, we use the following equation:

$$E[\gamma(G)] = E[S(G,v)]E[K(G,v)] + Cov[S(G,v), K(G,v)] \ . \qquad (6.4)$$

With regards to determining the expected secrecy, the expected degree is easily calculated for many types of random topologies. However, the *expected resilience* is much more difficult to calculate. We can apply Jenson's inequality [41] on the expected resilience measure to get a lower bound on the expected resilience. Let $E[\kappa(G)]$ be the expected vertex connectivity on a graph $G \in \mathfrak{G}_n$ on n nodes and let $E[\kappa(H(G,v))]$ be the expected connectivity of a survivor graph $H(G,v) \in H(\mathfrak{G}_n)$, where $H(\mathfrak{G}_n)$ is the set of survivor graphs generated from the removal of a random closed neighborhood from a graph in $\mathfrak{G}_n$. Then

$$\begin{aligned} E[K(G,v)] &= E\left[\frac{\kappa(H(G,v))}{\kappa(G)}\right] \\ &\geq \frac{E[\kappa(H(G,v))]}{E[\kappa(G)]} \quad . \end{aligned} \tag{6.5}$$

From here, we need to establish the closeness of this bound, look for ways to estimate the vertex connectivity, and determine the covariance between $E[S(G,v)]$ and $E[K(G,v)]$–all of which are dependent on the particular random graph process used.

6.2 Expected Global Subversion Impedance

Even in random topologies, we are still concerned about worst-case subversions. In assessing a randomized graph process, the expected global subversion impedance will measure the expected worst-case.

Definition 6.2.1. *The* expected global subversion impedance*, $E[\gamma^*(G)]$, is the expected value of the global subversion impedance, $\gamma^*(G)$, for all graphs $G \in \mathfrak{G}_n$;*

$$E[\gamma^*(G)] = \sum_{G \in \mathfrak{G}_n} \gamma^*(G) Pr(G) \quad , \tag{6.6}$$

where $Pr(G)$ is the probability of G being occurring within the family, $\mathfrak{G}_n$.

In the following, we analyze Erdös-Rényi and scale-free (Barabási-Albert) random graphs in order to determine their suitability as CCN topologies. We develop a closed-form estimate for the expected local subversion impedance for Erdös-Rényi random graphs.

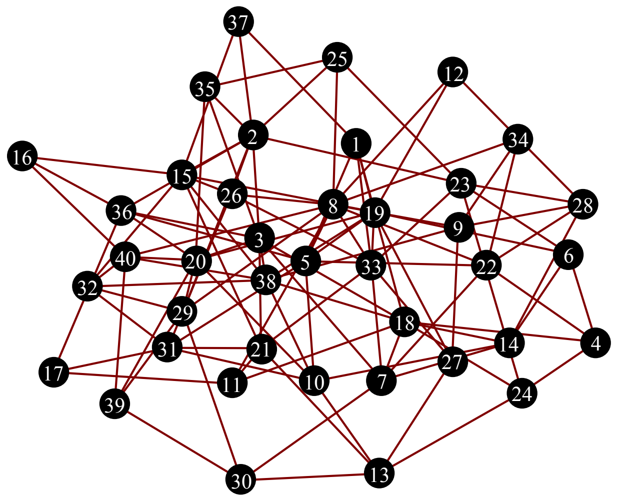


Figure 6.1: A $G_{n,p}$ random graph with $n = 40$ and $p = 0.15$.

6.3 Erdös-Rényi Random Graphs

Erdös-Rényi (ER) random graphs, or $G_{n,p}$ and $G_{n,M}$ graphs, are random undirected graphs with n nodes [5]. In $G_{n,p}$ graphs, each edge exists with an independent probability p. On the other hand, in $G_{n,M}$ graphs, M edges are selected, uniformly at random, from the $n(n-1)/2$ possible edges. Figure 6.1 shows a $G_{n,p}$ random graph generated with $n = 40$ and $p = 0.15$.

In both types of graphs, the edge degree is binomially distributed. Since the secrecy measure is a function of the node degree, the secrecy measure is also binomial. Thus, for a graph $G \in G_{n,p}$ and $s \in [0, 1]$, the probability that $S(G, v) = s$ is described by:

$$\begin{aligned} Pr(S(G,v)=s) &= Pr(d(v)=n-\psi-1) \\ &= \binom{n-1}{n-\psi-1} p^{n-\psi-1}(1-p)^{\psi} \quad , \end{aligned} \tag{6.7}$$

where $\psi = s(n-1)$. This gives the probability distribution of secrecy values across a graph $G \in G_{n,p}$. Since this is a discrete distribution, the value s must be chosen such that $\psi \in \mathbb{N}$. Otherwise ψ can be rounded off to the nearest integer.

Thus, we can calculate the expected secrecy from Equation 6.2:

$$\begin{aligned} E[S(G,v)] &= \frac{n - E[d(v)] - 1}{n} \\ &= \frac{n-(n-1)p-1}{n} \quad . \end{aligned} \tag{6.8}$$

These types of graphs are not guaranteed to be connected for small values of p and n. We assume that G is connected. In connected topologies that are either very sparse or verse dense, there is a high probability that the removal of a closed neighborhood can disconnect the network. In either case, $\gamma^*(G) = 0$.

6.3.1 Results for the Expected Local Subversion Impedance

Figure 6.2 shows the results of simulations to calculate the expected local subversion impedance for the $G_{n,p}$ graph process as n increases from 10 to 100 (increments of 5) for $p = 0.15$, $p = 0.25$ and $p = 0.35$. These results were generated by averaging over 100 simulations for each increment of n and p. The figure shows that the expected local subversion impedance is higher for the smallest value of p.

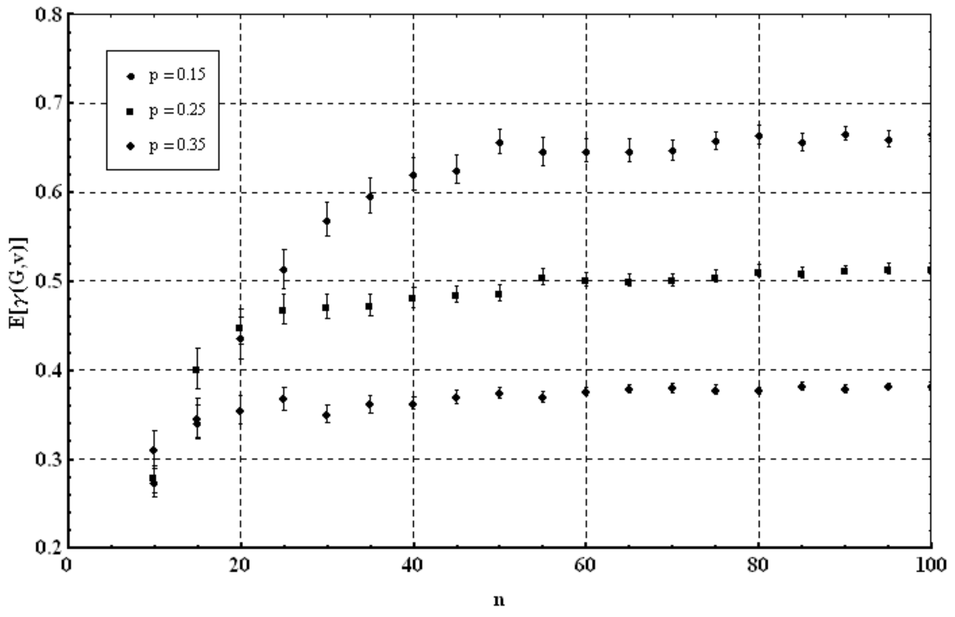


Figure 6.2: Comparison of the expected local subversion impedance among $G_{n,p}$ with increasing n and p. (95% CI)

When generating random graphs in our simulations, we discarded any $G \in G_{n,p}$ that was not connected. Of course, for low values of p and n, the higher the probability that the generated graph was disconnected, and discarded. While this may skew the results based on degree distribution and vertex connectivity, our measures are only meaningful is the starting topologies are connected. As n increases, even for low p, the probability that the generated graph is disconnected lowers, which results in a decreasing number of graphs being discarded, which in turn leads to less skew.

6.3.2 Results for the Expected Secrecy

Figure 6.3 shows the results of simulations to calculate the expected secrecy for the same values of p and range of n as above. The associated solid lines are the plots for Equation 6.8 for each value of p with increasing n. Notice that in each case, the simulation results quickly settle to the closed-form results. Unsurprisingly, the lower

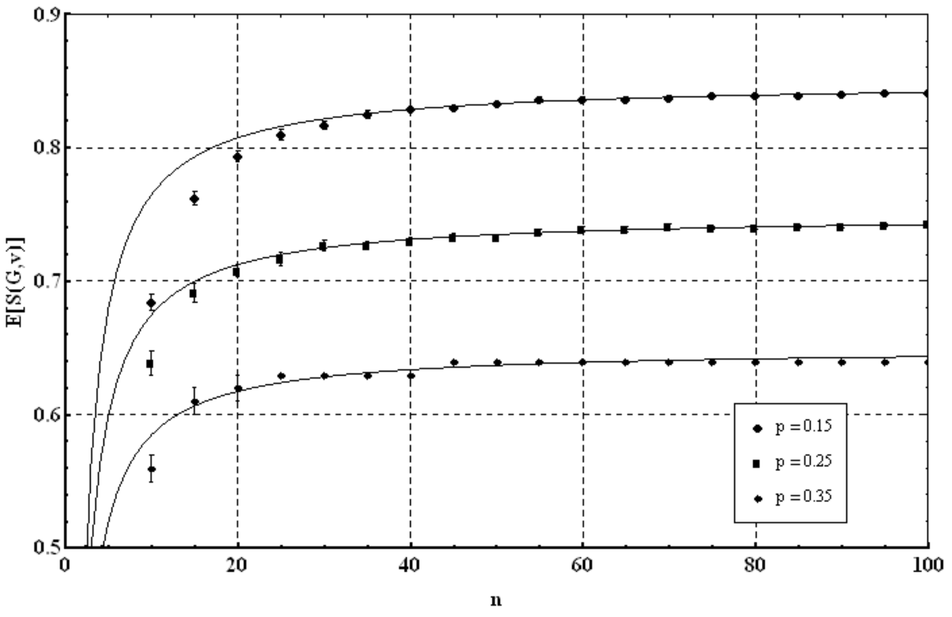


Figure 6.3: Comparison of the expected secrecy among $G_{n,p}$ with increasing n and p. (95% CI)

the value of p, the higher the expected secrecy since the neighborhoods within the topology are smaller.

6.3.3 Results for the Expected Resilience

Figure 6.4 shows the results of simulations to calculate the expected resilience for the same values of p and range of n as above. We see that the expected resilience, for $p = 0.15$, is initially the lowest value compared to the larger values of p shown. However, when $n \geq 30$, $E[K(G, v)]$ becomes highest when $p = 0.15$ (the smallest value of p tested).

Of course, determining the expected secrecy is computationally expensive given that the vertex connectivity must be calculated for the original topology, G, and every potential survivor graph, $H(G, v)$. Thus, if we could determine a closed-form equation for calculating the expected secrecy, we could evaluate $E[K(G, v)]$ for ar-

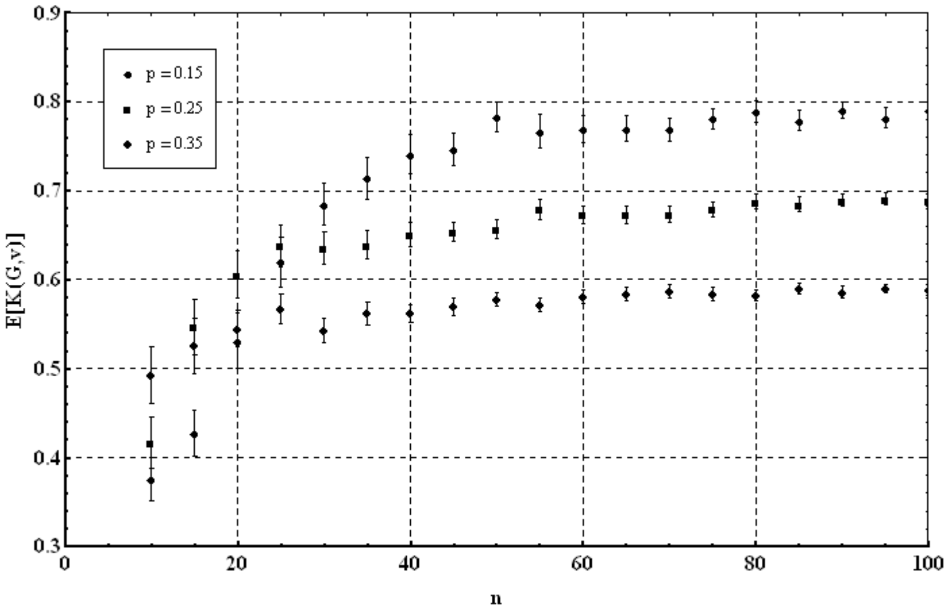


Figure 6.4: Comparison of the expected resilience among $G_{n,p}$ with increasing n and p. (95% CI)

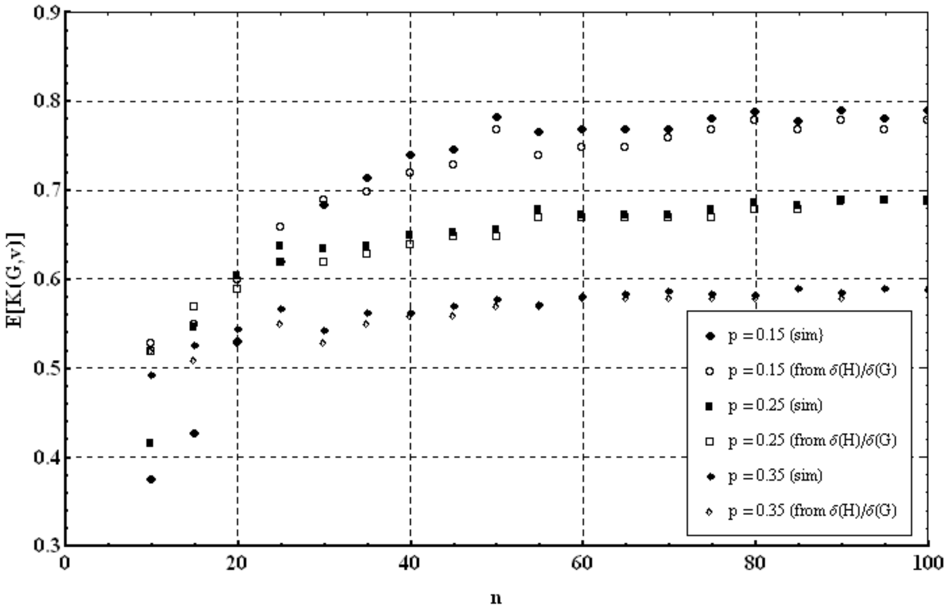


Figure 6.5: Comparison of the expected resilience determined from averaging the resilience of generated random graphs (solid plots) with the lower bound generated by Equation 6.9 (hollow plots).

bitrarily large topologies. A step in this direction would be to use the result from Bollobás that, for a fixed p, $0 < p < 1$, for almost every graph $G \in G_{n,p}$, $\kappa(G) = \delta(G)$ [5]. Now, we can modify Equation 6.5 to become

$$E[K(G,v)] \geq \frac{E[\delta(H(G,v))]}{E[\delta(G)]} \quad , \tag{6.9}$$

where $E[\delta(G)]$ and $E[\delta(H(G,v))]$ are the expected minimum degree for graph $G \in G_{n,p}$ and the survivor graph $H(G,v) \in H(G_{n,p})$, respectively. In Figure 6.5, the solid plots represent the simulation results for $E[K(G,v)]$, as in Figure 6.4. The hollow plots represent the lower bound of Equation 6.9. For the latter, $E[\delta(G)]$ and $E[\delta(H(G,v))]$ are determined by averaging the minimum degree from the graphs generated in the simulations for each p and n. From the simulation results, when $n = 100$, $E[\delta(H(G,v))]/E[\delta(G)]$ was within 1% of $E[K(G,v)]$ for all tested values of p. The lower bound is very tight and seems to converge to $E[K(G,v)]$ as n increases. Thus, Equation 6.9 seems to provide a good estimate for $E[K(G,v)]$.

6.3.4 Towards a Closed Form for $E[\delta(G)]$

Bollobás identifies several results related to vertex connectivity in $G_{n,p}$ and $G_{n,M}$ graphs in [5]. However, none of these results provided an approach for estimating the expected connectivity or the expected minimum vertex degree. We can, however, apply a series of results from order statistics [2], from which we can calculate the expected minimum from a set of n samples from a binomial distribution. For example, it is known that, for $G \in G_{n,p}$,

$$E[\delta(G)] = \mu_{1:n} = \sum_{x=0}^{n-1} [1 - F(x; n, p)]^n \quad , \tag{6.10}$$

where $F(x; n, p)$ is the cumulative distribution function (CDF) for the binomial dis-

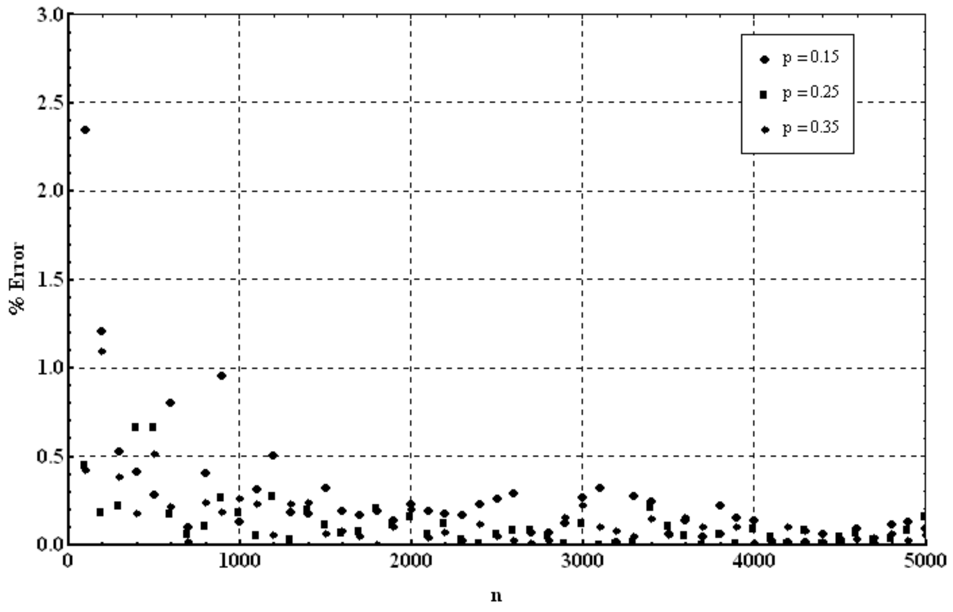


Figure 6.6: The error between the expected minimum degree derived from simulations and $\mu_{1:n}$.

tribution [2]. In this expression, the term $\mu_{1:n}$ is used to denote the expected smallest value in a sample of n elements.

Figure 6.6 shows the error between the calculated estimates from simulation, $E[\delta(G)]_{sim}$, and the expectation as calculated from Equation 6.10. For $n = 100$, the calculated estimates have an error of just over 2%, but which quickly falls off. For $n \geq 1000$, all test values ($p \in [0.15, 0.35]$) have an error of less than 1%. In fact, with these results, we assume that, as n increases,

$$\frac{|E[\delta(G)]_{sim} - \mu_{1:n}|}{E[\delta(G)]_{sim}} \to 0 \quad . \tag{6.11}$$

Using Equation 6.9 gives us a good estimate for $E[\delta(G)]$ for large n, but what about $E[\delta(H(G,v))]$? We know the expected number of nodes in $H(G,v)$, but does Equation 6.9 still give a good estimate for the connectivity of the survivor graph?

Theorem 6.3.1. *Let $G(V,E) \in G_{n,p}$ for $n \geq 1$ and $p \in [0,1]$, and let $H(G,v) \subset G$ be the survivor graph resulting from $G - N[v]$ for some vertex $v \in V$. Then, $H(G,v) \in G_{n',p'}$ with*

$$n' = n - E[d(v)] - 1 \quad , \tag{6.12}$$

and

$$p' \to p \quad , \tag{6.13}$$

as $n \to \infty$.

Proof. The expected number of nodes in the closed neighborhood of v is $E[d(v)] + 1$, with

$$E[d(v)] = (n-1)p \approx np \quad , \tag{6.14}$$

for large n. Thus, the expected number of nodes, n', in $H(G,v)$ is the number of nodes in G minus the expected size of the closed neighborhood:

$$|H(G,v)| = n' = n - E[d(v)] - 1 \quad . \tag{6.15}$$

The expected number of edges, M, in G is:

$$M := E[||G||] = \frac{n(n-1)}{2}p \quad .$$

If the nodes within the closed neighborhood shared no edges, we could expect $N[v]$ to have $E[d(v)]^2$ edges. However, at least some of the nodes in the closed neighborhood may have been connected and therefore share edges, so we must be sure not to double-count the portion of edges connecting edges within $N[v]$. Thus, the expected number of edges, e_N within $N[v]$ is

$$e_N := E[||N[v]||] = E[d(v)]^2 - \frac{E[d(v)](E[d(v)]-1)}{2}p \quad ,$$

allowing the expected number of edges remaining, M', in $H(G,v)$ to be

$$M' = E[||H(G,v)||] = M - e_N \quad .$$

Since any $G \in G_{n,p}$ has a binomial degree distribution with the presence of each edge determined independently, the removal of the set of edges in $N[v]$ results in a degree distribution in $H(G,v)$ that is still binomially distributed. This tell us that $H(G,v)$ is an Erdös-Rényi (ER) random graphs, thus, $H(G,v) \in G_{n',p'}$ for n' as in Equation 6.15 and p' as

$$\begin{aligned} p' &= \frac{2M'}{n'(n'-1)} \\ &\approx \frac{2(M-e_N)}{(n-np-1)(n-np-2)} \\ &\approx p\left[\frac{n^2-n-2n^2p+n^2p^2-p}{(n-np-1)(n-np-2)}\right] \quad . \end{aligned}$$

Thus, $p' \to p$ since

$$\lim_{n\to\infty} \frac{n^2-n-2n^2p+n^2p^2-p}{(n-np-1)(n-np-2)} \to 1 \quad . \tag{6.16}$$

□

In fact, for most values of p, p' quickly approaches p for relatively low values of

n. Table 6.1 shows that for $p \leq 0.8$, networks with less than 100 nodes are already very close to to the limit in Equation 6.16.

Table 6.1: Error (difference) between p and p'

n \ **p**	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	0.27	0.28	0.29	0.28	0.21	0.10			
50	0.04	0.05	0.05	0.05	0.04	0.02	0.04	0.32	
100	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.13	
500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.15

Thus, given the expected number of nodes in the survivor graph and the value for p, we can calculate an estimate for $E[\delta(H(G,v))]$ which improves as n grows. Now, we show how to use the estimates developed above to develop a closed-form estimate for $E[\gamma(G,v)]$.

6.3.5 *Towards a Closed Form Estimate for $E[\gamma(G,v)]$*

With the results above, we use Equation 6.10 to estimate $E[\delta(H(G,v))]$. With this estimate and the closed-form estimate for $E[\delta(G)]$, we can calculate a closed-form lower bound using Equation 6.9

$$\begin{aligned} E[K(G,v)] &\geq \frac{E[\delta(H(G,v))]}{E[\delta(G)]} \\ &\geq \frac{\mu_{1:n'}}{\mu_{1:n}} \\ &\geq \frac{\sum_{x=0}^{n'-1}[1-F(x;n',p)]^{n'}}{\sum_{x=0}^{n-1}[1-F(x;n,p)]^{n}} \quad , \end{aligned} \tag{6.17}$$

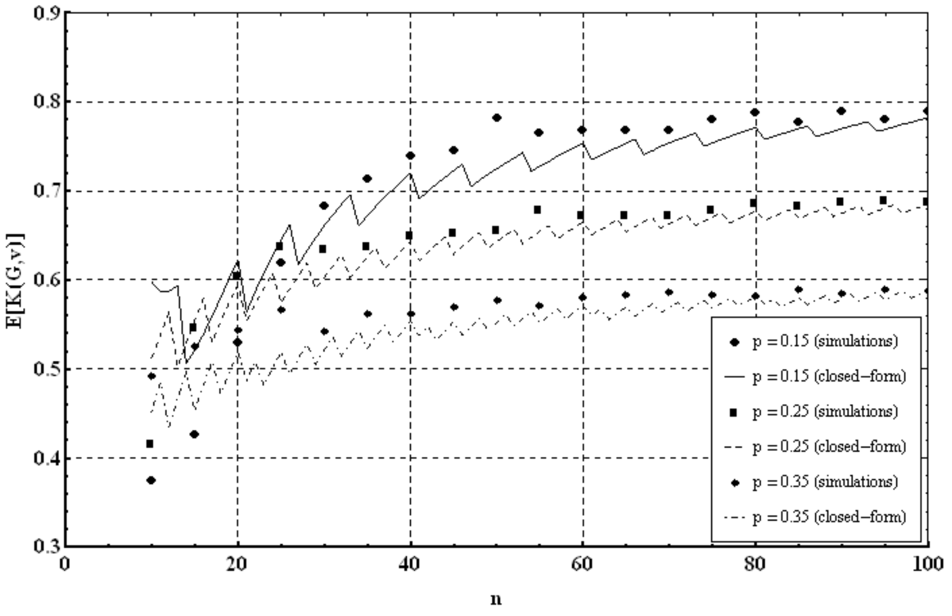


Figure 6.7: Comparison of the expected resilience with the closed-form estimates.

where $\mu_{1:n'}$ denotes the expected minimum value of the connectivity over the n' nodes in the survivor graph where $n' = n - E[d(G)] - 1 = n - \lceil n \times p \rceil - 1$ (we use the ceiling function to preserve the lower bound). In fact, the simulation results seem to indicate that $|E[K(G, v)] - (\mu_{1:n'}/\mu_{1:n})| \to 0$ as $n \to \infty$.

Figure 6.7 plots the comparison of the values for $E[K(G, v)]$ (hollow plots, which are the same as shown in Figure 6.4), with the closed-form estimates calculated using Equation 6.17 (solid plots). We see the lower bound hold for $n \geq 30$, and as n increases, we see a convergence between the two plots.

Referring back to Equation 6.4, we have closed-form equations for $E[S(G, v)]$ (Equation 6.8) and $E[K(G, v)]$ (Equation 6.17). We now examine the covariance between these two values. Figure 6.8 shows the expected covariance as calculated from simulations generated as the average of 100 simulations for each value of p and range n with n incremented by 10 at each step. First, the results show that the

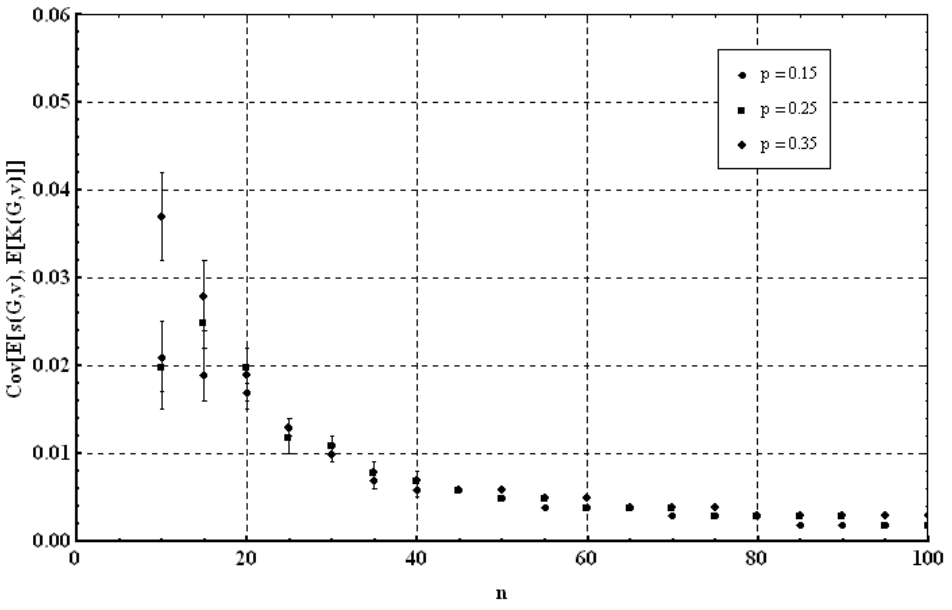


Figure 6.8: Average covariance for graphs in $G_{n,p}$ with $10 \leq n \leq 100$ and $p = 0.15$, $p = 0.25$, and $p = 0.35$, respectively. (95% CI)

covariance is positive. Given this result and Equation 6.17, we have

$$E[\gamma(G, v)] \geq E[S(G, v)] \times E[K(G, v)] \quad . \tag{6.18}$$

Second, the results show that the covariance seems to be independent of p as the plots for each p and each n seem to be identical. Third, as n increases, the covariance decays at an exponential rate. For $G \in G_{n,p}$ with $n > 30$, $Cov[E[S(G, v)], E[K(, v)]] < 0.01$. Thus, as n increases, the expected secrecy and expected resilience seem to become more and more independent. Thus, assuming that $Cov[E[S(G, v)], E[K(G, v)]] \to 0$ and $|E[K(G, v)] - (\mu_{1:n'}/\mu_{1:n})| \to 0$ as $n \to \infty$, we have

$$E[\gamma(G, v)] \to E[S(G, v)] \times E[K(G, v)] \quad . \tag{6.19}$$

Figure 6.9 shows the results between the expected local subversion impedance,

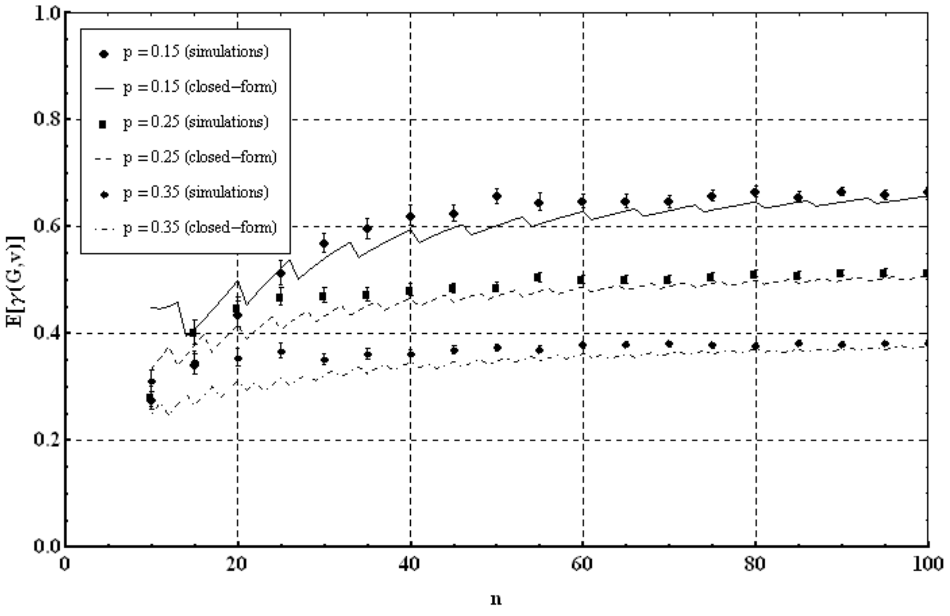


Figure 6.9: Comparison of the expected local subversion impedance derived from simulations (95% CI) with the closed-form estimates.

$E[\gamma(G, v)]$, averaged from simulations and the closed-form estimate from Equation 6.19. Figure 6.10 displays the error of the closed-form estimate off of the value averaged from simulations. We see a quick convergence between these two values for topologies as small as $n = 30$ (less than 10% error). At $n = 100$, we have only 1% error between the simulation results and the closed-form estimate.

6.3.6 Results for the Expected Global Subversion Impedance

Whereas the estimate for $E[\delta(G_{n,p})]$ derived above works well as a basis for estimating $E[\gamma(G_{n,p})]$, it will not suffice for estimating the expected global subversion impedance. An approach for a closed-form estimate for $E[\gamma^*(G_{n,p})]$ could use an approach similar to that used above, but the focus would need to be on finding a good estimate for $E[\delta(H(G, v^*))]$.

In Figure 6.11, the expected global subversion impedance is shown as calculated

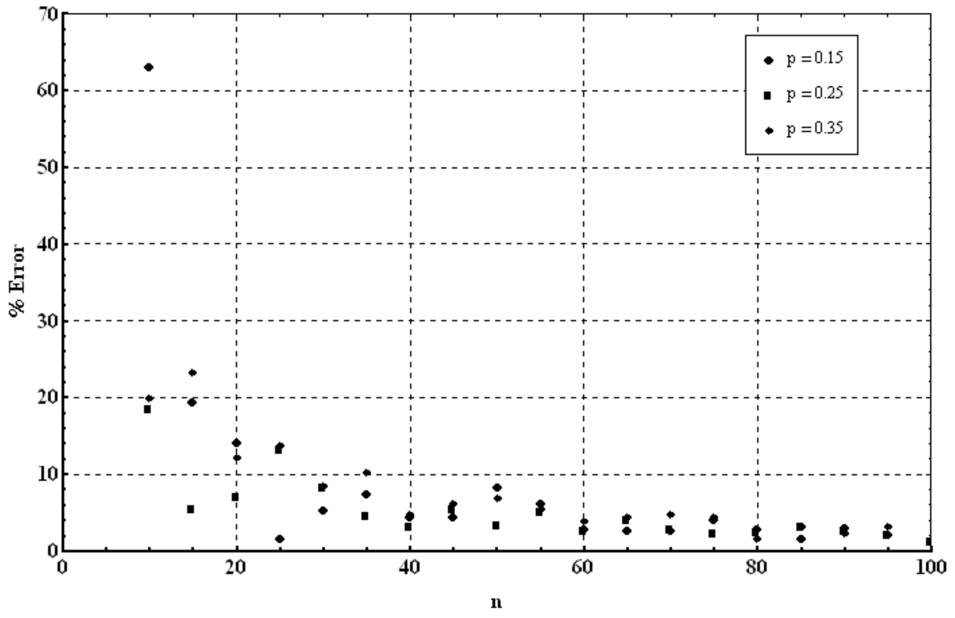


Figure 6.10: The error between the expected local subversion impedance derived from simulations and the closed-form estimates.

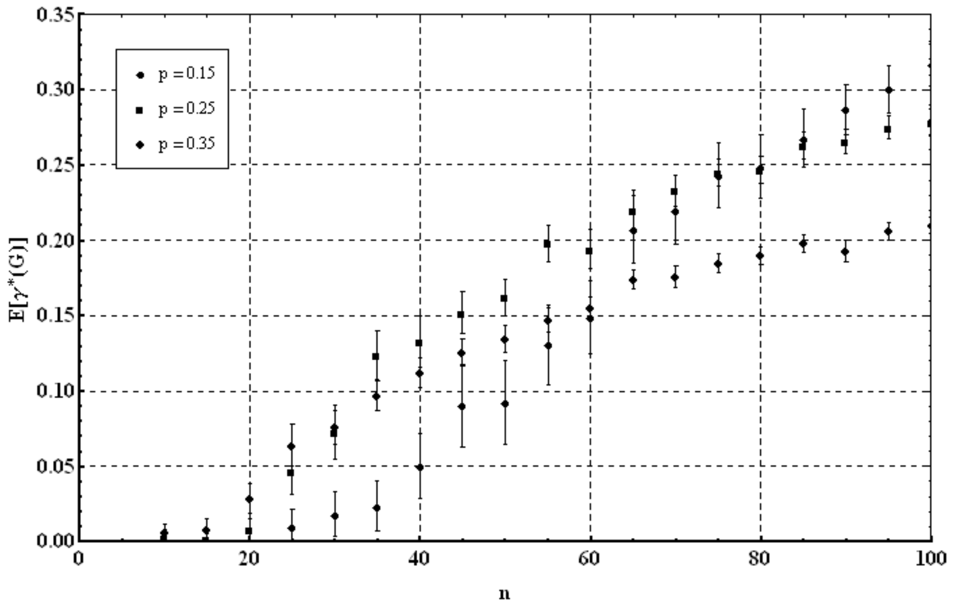


Figure 6.11: Comparison of the expected global subversion impedance among $G_{n,p}$ with increasing n and p. (95% CI)

based on simulations (the average of 100 randomly generated, connected graphs from $G_{n,p}$ with, as before, $10 \leq n \leq 100$ and $p = 0.15$, $p = 0.25$, and $p = 0.35$, respectively. We see that when $n \leq 60$, $E[\gamma^*(G_{n,p})]$ is lowest when $p = 0.15$. However, as n continues to increase, a low value for p proves to be best.

6.4 Scale-free Random Graphs

A scale-free network is one in which the degree distribution decays as a Pareto distribution or power-law. Among others, social networks, biological networks, and hyperlink connectivity on the World Wide Web are conjectured to be scale-free. In the construction of membership-concealing overlay networks (MCONs), Vasserman relies on existing real-world relationships to establish connectivity within the MCON [61]. This approach prevents any participant within the network from gaining any new knowledge about other participants (i.e., prevents participants from increasing their network promiscuity). The resulting topology should resemble a scale-free network. We now examine these topologies in order to determine if their structure is suitable for CCNs.

Albert-László Barabási and Réka Albert developed the most commonly used approach for modeling random, scale-free networks [3]. Known as BA graphs, the model starts with m_o connected nodes. At every time step t a new node is added to the network and connected to m existing nodes. Thus, $t = n - m_o$. We denote the family of BA constructed graphs on n nodes and m edges per time step as $G_{BA}(n, m)$. The probability $Pr_i(t)$ that the new node is connected to node i at time t depends on the degree $d_t(i)$ of node i such that

$$Pr_i(t) = \frac{d_t(i)}{\sum_{k=1}^{t-1} d_t(k)} \quad .$$

This is known as preferential attachment. As shown in [4], building topologies with

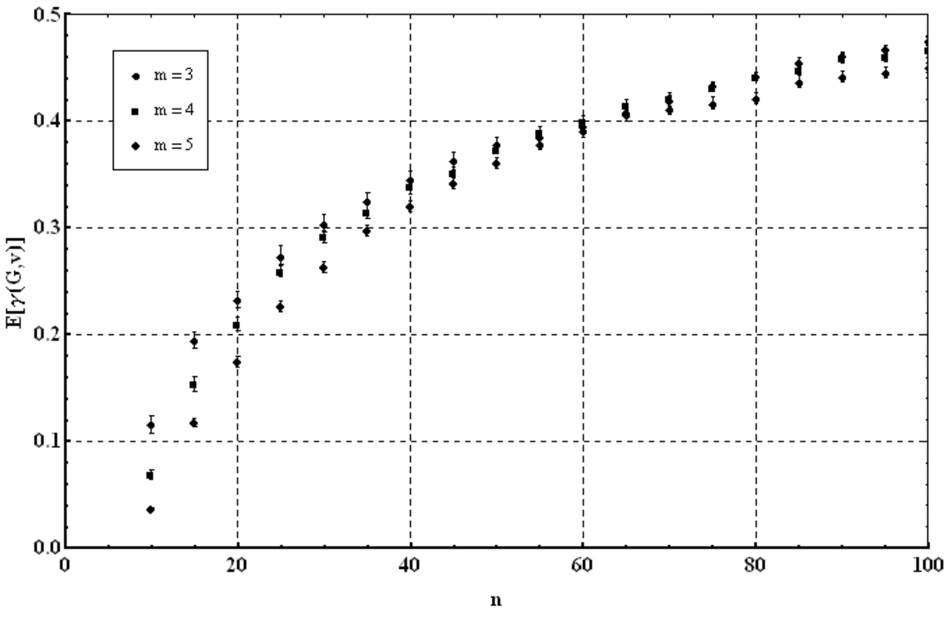


Figure 6.12: The expected local subversion impedance for BA topologies with $3 \leq m \leq 5$. (95% CI)

this approach gives a node degree distribution at the end of the evolution of

$$\begin{aligned} Pr(d(v) < x) &= 1 - \frac{m^2 t}{x^2 n} \\ &= 1 - \left[\frac{x}{\left(\frac{m\sqrt{t}}{\sqrt{n}}\right)} \right]^{-2} \quad . \end{aligned}$$

This is a Pareto distribution. Thus, the expected degree of a node i at time t is

$$E[d(v)] = \frac{2m\sqrt{t}}{\sqrt{n}} \quad . \tag{6.20}$$

Thus, we can calculate the expected secrecy for $G \in G_{BA}(n, m)$ as:

$$E[S(G,v)] = \frac{n - \left[\frac{2m\sqrt{t}}{\sqrt{n}}\right] - 1}{n} \tag{6.21}$$

For the expected resilience, we need the expected connectivity of the original graph, $G \in G_{BA}$, and the expected connectivity of the survivor graph, $H(G, v)$, using the BA construction. The expected connectivity of the original topology is equal to the expected minimum degree,

$$E[\kappa(G)] = E[\delta(G)] \quad .$$

The expected connectivity of the survivor graph is much less clear. Unfortunately, we can't use the same approach to calculate the expected connectivity of the survivor graph that we used earlier for Erdös-Rényi graphs because the survivor graph is no longer a scale-free graph.

Figure 6.12 shows the expected local subversion impedance for $10 \leq n \leq 100$ where each plot is the mean of 100 randomly generated topologies at a given order and the order is increased by 5 at each step. We see that these topologies perform moderately well in the average case with an expected local subversion impedance at around $E[\gamma(G)] \approx 0.47$ for the values of m that we examined ($3 \leq m \leq 5$). Unfortunately, in the worst case, these topologies were almost always disconnected resulting in $E[\gamma^*(G_{BA})] \approx 0$ for $3 \leq m \leq 5$ and $n \leq 100$. As n and m increase, the probability that the survivor graph remains connected also increases, but not at a rate that showed any promise for the use of scale-free graphs in CCNs.

6.5 Conclusions

Our analysis was motivated by [1], in which Réka Albert, Hawoong Jeong, and Albert-László Barabási compare the effects of random and worst case attacks in Erdös-Rényi random graphs and scale-free random graphs as single nodes are removed. Likewise, we examine the effects of neighborhood failures on these same two families of random graphs in both the random and worst case.

In the previous sections, we defined measures for assessing the suitability of a random topology for a CCN. With these measures, we analyzed Erdös-Rényi Random Graphs and scale-free graphs from the Barabási-Albert construction. We also determined a closed form estimate for the expected local subversion impedance of $G_{n,p}$ graphs and a closed form estimate for the expected secrecy of a BA topology. For the parameters examined, the expected local subversion impedance in $G_{n,p}$ topologies was significantly higher than that of BA topologies. BA topologies also have very poor expected global subversion impedance. The homogenous nature of $G_{n,p}$ graphs make them less vulnerable to catastrophic damage resulting from subversions.

7. MEMBERSHIP MANAGEMENT IN A COVERT COMMUNICATION NETWORK

Joining a covert communications network (CCN) is risky both for the network participants as well as for the prospective participant. The existing network participants want a discerning way to protect against adversarial infiltration. A prospective participant will want to make sure that the CCN it is joining is legitimate and that he will not be placed at an inordinate risk by the other network participants. Therefore, a *join protocol* has to be in place that enables prospective nodes to join the network while preserving membership concealment.

We are interested in protocols that allows nodes to join the network in a manner that: (1) protect against unnecessary exposure of the identity of each participating node; (2) do not generate a large communication signature–that is, members of a CCN should not be identified as such by their communication patterns; and (3) do not rely on the secrecy of either the software or protocols used.

7.1 Initial Vetting and Shared Credentials

Traditional P2P networks are not concerned with membership concealment and, therefore, are open to anyone who wishes to join. Often, the network addresses of existing nodes are publicly advertised in order to provide a point of connectivity for new nodes. When a new node wants to join, it connects to an existing node, and the address information of the new node is shared across the network in a promiscuous manner allowing other nodes to establish direct connections to the new node or establish direct connections to other existing nodes according to their topology management scheme (e.g., CAN [51] and Chord [57]). Even in anonymity networks such as [16, 21, 23, 52], membership concealment is not addressed. As a result, nodes in such systems display network promiscuity, which affects membership concealment and provides easy ways of infiltration for an adversary interested in discovering the network addresses of participants.

An exception is Membership-Concealing Overlay Networks in which Vasserman *et al.* restrict direct connections within the network topology to those that already exist in personal relationships [61]. This approach is limiting, however, in that it does not allow direct connections to be established between participants that do not know each other already and thus limits the topology and the growth of the network. For the network to grow, a mediation mechanism must be in place that allows previously unrelated nodes to enter into a trust relation that allows for establishment of a direct connection. Typically, one would have to rely on some out-of-band mechanism that provides a baseline of trust between the network participants and the prospective participant and allows the exchange of credentials needed to connect the new node to the existing network. Ideally, in a CCN, we would like an approach that does not require an out-of-band communication between the current CCN participants and a prospective participant. However, we are unaware of an approach that would protect against adversarial infiltration of the CCN without some sort of shared secret between the new prospect and an existing CCN participant. Therefore, we must assume that some form of vetting (for example, as part of a separate recruiting process) restricts membership to only those that possess the shared secret.

7.2 First Contact

We distinguished between the *participant*, the participant's *node*, v_i, and the node's *pseudonym*, P_i, we also specify the network address of the node, A_i. Thus, if node, v_j is a neighbor to v_i within the CCN topology, then v_j knows node v_i's address, A_i. We consider *first contact* to be the event in which a *current node*, v_{curr}, within the CCN establishes direct communication with the *new node*, v_{new}, that is joining the CCN. The current node is, of course, the network presence of a participant already connected within the network; while, the new node is the network presence of the prospective participant. The current node is connected to other nodes within the CCN, and the new node is not yet connected to the CCN. The connection between the two nodes, v_{curr} and v_{new}, is established by each node revealing their network address, A_{curr} and A_{new} respectively, to each other resulting in an increase in both nodes' network promiscuity.

7.2.1 Current Node Determination

For ease of description, we assume that each node in the network is able, if required, to determine the set of current nodes, V_{curr} that will establish direct connections to the new node. Among this set, V_{curr}, the current node, $v_{curr} \in V_{curr}$ that will establish first contact can be arbitrarily selected based on the needs of the network. The newest node from V_{curr} may be selected and thus exposed to more risk on the basis that it is more expendable. On the other hand, the same logic can be used to argue that the newest node is the least trustworthy. Thus, the oldest node may be selected as v_{curr}. A third option would be to choose a random node from V_{curr} to act as v_{curr}. Of course, this approach would require agreement from all nodes within V_{curr}.

7.2.2 Direct First Contact

A naive approach for first contact would allow the new node to contact the current node directly. The credentials provided to the new node may contain the network address for a current member of the network, allowing the new node to directly connect to the current member. Assuming that traffic is secured via asymmetric encryption, the new node requires the public key of the current node to be provided as part of the “out-of-band” credentials. The risk associated with this approach is that the network address of the current node is being provided “in-the-clear”. If the new node does not follow-up and use the information to establish the connection, the network promiscuity of the current node just increased without tangible benefit to the network. In addition, the CCN still must manage the topology as if the current node was connected to the new node. This approach seems to place an inordinate risk on the current node through the potential for premature exposure. A method must be devised that avoids the type of exposure.

7.2.3 Indirect First Contact

We prevent premature exposure of the address, A_{curr}, of node v_{curr} by pushing the associated risk to the new node. In this approach, the new node is provided with the reference to a public repository that allows some form of information sharing (e.g. Flickr or Facebook) and half of an asymmetric key. The new node encrypts its network address using the provided key, and uploads it to the repository. The current node has the other half of the asymmetric key pair. The current node checks the repository to detect the presence of the uploaded information, downloads the payload, and uses its half of the key pair to decrypt the network address of the new node. Then, the current node uses that information to establish direct connectivity with the new node.

In this approach, the current node is not at risk of premature exposure, and the new node assumes an initial level of risk that is on par with other CCN nodes. Once first contact is made between the current node and the new node, the current node passes its knowledge of the CCN to the new node (i.e., the public keys of all known CCN nodes). This allows the new node to calculate with which other current nodes that it needs to establish connections (i.e., V_{curr}). Then, the new node can request to establish direct connections with the appropriate nodes.

7.3 Basic Join Protocol

The following two protocols provide the basic mechanism for a potential participant to join a CCN. The first protocol focuses on establishing first contact between the potential participant and the CCN, and the second protocol is to establish additional connections between the new node and the CCN. Both protocols accomplish their functions in a manner that prevents unnecessary increases in network promiscuity.

7.3.1 Protocol 1 - First Contact

The purpose of the following protocol is to establish first contact between v_{new} and v_{curr}. Once complete, v_{new} will be connected to the CCN and have v_{curr} as its only neighbor.

A-1. The new prospect instantiates node, v_{new} with a network address, A_{new}, and key pair $(K^{pub}_{new}, K^{pri}_{new})$.

A-2. Node v_{new} has a pseudonym, P_{new}, half of an asymmetric key pair, K^A, and the repository location, L_{share}–provided out-of-band.

A-3. The current node v_{curr} has a pseudonym, P_{curr}, a network address, A_{curr}, the repository location, L_{share}, and the other half of an asymmetric key pair, K^{-A}, such that, for a message, M,

$$K^A(K^{-A}(M)) = K^{-A}(K^A(M)) = M \quad .$$

A-4. Node v_{new} encrypts its pseudonym and network address, $K^A(P_{new}, A_{new}, K^{pub}_{new})$ and uploads the encrypted data to L_{share}.

A-5. Node v_{curr} periodically checks L_{share}, and, when detected, downloads from L_{share}

$$K^A(P_{new}, A_{new}, K^{pub}_{new}) \quad . \tag{7.1}$$

A-6. Node v_{curr} decrypts $K^{-A}(K^A(P_{new}, A_{new}, K^{pub}_{new}))$, adds (P_{new}, K^{pub}_{new}) to its key table, adds (P_{new}, A_{new}) to its routing table, and adds A_{new} to its list of neighbors,

$$N(v_{curr}) = \{\cdots, A_{new}\} \quad .$$

A-7. Node v_{curr} sends a connect request, $K^{pub}_{new}(P_{new}, P_{curr}, C_r, A_{curr}, K^{pub}_{curr})$ to node v_{new}.

A-8. Node v_{new} receives and decrypts the connection request from v_{curr} and, if v_{curr} is the expected node in accordance with the desired topology, sends a connection accept to v_{curr},

$$K^{pub}_{curr}(P_{curr}, P_{new}, C_a) \quad ,$$

adds $(P_{curr}, K^{pub}_{curr})$ to its key table, add (P_{curr}, A_{curr}) to its routing table, and adds A_{curr} to its list of neighbors,

$$N(v_{new}) = \{A_{curr}\} \quad .$$

A-9. Node v_{curr} receives and decrypts $K^{-A}(K^A(P_{curr}, P_{new}, C_A))$ and exchanges additional channel information and generates symmetric keys with v_{new}, as desired.

At the end of Protocol 1, nodes v_{curr} and v_{new} are connected. We can now proceed to connecting v_{new} to additional nodes in the network, according to the topology requirements of the CCN.

7.3.2 Protocol 2 - Increasing Connectivity

Picking up where Protocol 1 ends, we assume that we have node v_{curr} connected to node v_{new}. Node v_{new} has no other neighbors within the CCN. The goal of this step is to establish direct connectivity between v_{new} and all other nodes, v_j, within the CCN with which it is supposed to be neighbors, V_{curr}.

B-1. Node v_{curr} sends a copy of its key table, T_{keys} to node v_{new} in which, for all nodes, v_i, in the CCN,

$$T_{key} = \{P_i, K_i^{pub}\} \quad ,$$

where P_i is the pseudonym and K_i^{pub} is the public key of v_i.

B-2. Based on the number of participants within the network, $|T_{key}|$ and the desired topology, node v_{new} generates the set of pseudonyms, P_j, corresponding to the set of nodes, $v_j \in V_{curr}$, to which it should connect.

B-3. For each node, $v_j \in V_{curr}$, v_{new} encrypts and sends a connection request to v_j (routed through v_{curr}),

$$K_j^{public}(P_j, P_{new}, C_r, A_{new}, K_{new}^{public}) \quad ,$$

in the same manner as Protocol 1: Step A-7.

B-4. Each node v_j receiving a connection request from v_{new} decrypts the request and determines if it should be connected to v_{new}. If so, v_j sends a connection accept to v_{new} and adds v_{new} to its list of neighbors in the same manner as in Protocol 1: A-8, above.

B-5. Node v_{new} exchanges additional channel information and generates symmetric keys with each neighbor, v_j, as desired.

At this point, the node v_{new} is a member of the CCN. We will now proceed to analyze the resilience of the join protocol against a number of attacks.

7.4 Attacks Against the Basic Join Protocol

7.4.1 Man-in-the-Middle Attacks

Unfortunately, the approach described above is vulnerable to a man-in-the-middle attack when the current node establishes first contact. Node v_{curr} could corrupt the process by mimicking the join process in such a way that the multiple connections established by the new node are, in fact, all with node v_{curr}.

7.4.2 Sybil Attack

The approach above is vulnerable to a limited Sybil attack by v_{curr}. The current node could create a fictitious v_{new} and, thus, gain knowledge of the set of addresses from all other nodes that become neighbors with v_{new}, thus undermining the membership concealment of the CCN.

Careful selection of v_{curr} will mitigate this vulnerability. Selecting v_{curr} as the oldest node in V_{curr} insures that, arguably, the most trustworthy node is the one selected to establish first contact. In this approach, a limited set of nodes will act as v_{curr} relative to the number of nodes within the network. On the other hand, selecting the newest node as v_{curr} means that the same node will only act in that capacity once, thus limiting the rate of infiltration by false nodes.

Use of a recruiter separate from the participant operating v_{curr} will mitigate the participant's ability to add a false node (assuming a trustworthy recruiter), but moves the threat of a Sybil attack to the recruiter. Groups using a CCN will need to decide where they are most vulnerable and where they would rather incur risk.

7.4.3 Collusion Attack

Assuming that the join protocol was executed without subversion, multiple nodes could collude to undermine the anonymity of the network by sharing the addresses of their topological neighbors. However, though individual nodes may gain information about participants, there is no net gain in information from the colluding nodes. Without loss of generality, we treat colluding nodes as multiple, independent subversions.

7.5 Distributed Join Protocol

In order to mitigate attacks from v_{curr}, we can modify Protocol 1 in Section 7.3.1 and Protocol 2 in Section 7.3.2 so that each node v_j (and no others) shares K^{-A} and L_{share}. Then, each node v_j individually downloads $K^A(P_{new}, A_{new}, K^{pub}_{new})$ from L_{share}, decrypts it, and sends v_{new} a connection request. This allows each node v_j to independently connect to v_{new} instead of using v_{curr} as the intermediary.

7.6 Generating the Shared-Secret

Protocol 1 and Protocol 2 started with the nodes v_{curr} and v_{new} already in possession of their portion of the necessary credentials, that is, the shared-secret was already generated and shared. The following two protocols assume the existence of a recruiter node, v_R, providing the communication transfer point between the network and the out-of-band channel.

7.6.1 Protocol 3 - Single Node Shared-Secret Generation

The following describes the protocol for the recruiter node, v_R, to request the credentials from v_{curr} that will be sent out-of-band to the new prospect.

C-1. Node v_{curr} generates:

- the pseudonym for the new node, P_{new};
- the asymmetric key pair, (K^A, K^{-A}); and
- the repository location, L_{share}.

C-2. The recruiter node, v_R, sends a shared-secret request, S_R, to v_{curr} as

$$K_{curr}^{pub}(P_{curr}, P_R, S_R) \quad .$$

C-3. Node v_{curr} encrypts and sends the response, S_D, to v_R, as

$$K_R^{pub}(P_R, P_{curr}, S_D, P_{new}, K^A, L_{share}) \quad .$$

C-4. Node v_R receives and decrypts P_{new}, K^A and L_{share}.

C-5. The recruiter passes P_{new}, K^A and L_{share} out-of-band to the prospect.

At the end of this protocol, the recruiter possesses the credentials that he will pass to the new prospect via the out-of-band channel. Once the new prospect has the credentials, then Protocol 1 can be followed.

7.6.2 Protocol 4 - Distributed Shared-Secret Generation

The distributed join protocol described in Section 7.5 requires a distributed protocol for generating the shared-secret. The following describes the agreement protocol between the elements in V_{curr} and v_R on the set of credentials to be communicated to v_{new}.

D-1. Let V bet the set of connected nodes in the CCN, and let v_{new} be the unconnected new node that will join the network. Let $V_{curr} = \{v_j \in V\} \subseteq V$ be the set nodes that will connect to v_{new}. Finally, let $v_{curr} \in V_{curr}$ be an agreed upon node in V_{curr}.

D-2. Node v_{curr} generates:

- the pseudonym for the new node, P_{new};
- the asymmetric key pair, (K^A, K^{-A}); and
- the repository location, L_{share}.

D-3. The recruiter node, v_R, requests P_{new}, K^A and L_{share} from v_{curr} with S_R.

D-4. Node v_{curr} encrypts and sends to all other $v_j \in V_{curr}$,

$$K_j^{pub}(P_j, P_{curr}, S_D, P_{new}, K^A, L_{share}) \quad .$$

D-5. Node v_{curr} encrypts and sends to v_R, the response

$$K_R^{pub}(P_R, P_{curr}, S_D, P_{new}, K^A, L_{share}) \quad .$$

D-6. Node v_R receives and decrypts P_{new}, K^A and L_{share}.

D-7. Node v_R encrypts and sends to all $v_j \in V_{curr}$,

$$K_j^{pub}(P_j, P_R, S_D, P_{new}, K^A, L_{share}) \quad .$$

D-8. Each node $v_j \in V_{curr}$ receives, decrypts, and compares the results they received from v_{curr} and v_R. If the results match, they each respond S_D. Otherwise, to both v_R and all other v_j, they respond with an error flag, E_R.

D-9. The recruiter passes P_{new}, K^A and L_{share} out-of-band to the prospect.

At the end of this protocol, all members $v_j \in V_{curr}$ possess the needed credentials to independently check the repository for the arrival of v_{new} and the recruiter possesses the credentials that he will pass to the new prospect via the out-of-band channel. Once the new prospect has the credentials, then the distributed join protocol can be followed.

7.7 Attacks Against the Distributed Join Protocol

The distributed join protocol protects against the attacks described earlier by forcing distributed checks and balances between nodes. The network does become more vulnerable to many of these same attacks by the recruiter v_R, but now the problem is one of robust out-of-band vetting of the recruiter. Appropriate vetting is then controlled by policy to address the needs of the CCN.

7.7.1 Dealing with Node Departure or Node Failure

Given the need to restrict network promiscuity and protect membership concealment, traditional approaches to network healing are not allowed. Thus, stopped or failed nodes need to rejoin the network in the same location within the topology. For low-latency requirements, sufficient nodes need to be active to maintain a connected topology with low network distance between the communicating nodes. Thus, failed nodes would need to quickly reset and rejoin the network. Of course, if the CCN is restricted to high-latency communication, then it is delay-tolerant. In a delay-tolerant CCN, nodes have much more flexibility in how long they can be dormant.

7.8 Conclusions

Joining a CCN is more complicated than joining a P2P network not concerned with both membership concealment and resiliency. While no known protocol is known that will eliminate the risk of all participants, the protocols examined attempt to minimize the exposure of the participants to a powerful adversary. Through proper vetting of prospective participants, distributed checks and balances between nodes, and minimizing network promiscuity, groups can protect both themselves and their communication.

8. ROUTING IN A COVERT COMMUNICATION NETWORK

Routing across a CCN relies on the use of pseudonyms as the logical address and relies on the type of topology used. Topologies are considered either deterministic or random. Deterministic topologies are those in which the connections between nodes are deterministically determined, and similarly, random topologies are those in which the connections between nodes are randomly determined. We examined deterministic construction approaches in Sections 4 and 5. We examined random constructions in Section 6. In this section, we examine approaches to routing in CCNs. First, we provide an overview of some general algorithms that work regardless of the overlay topology. Then, we describe approaches for routing in deterministic topologies with specific algorithms for the Gunther-Hartnell and Extended Robertson construction topologies.

8.1 General Approaches to Routing

CCN messages are routed across the network from the source node, v_s, to the destination node, v_d, by relying on intermediate nodes to forward traffic through the network. Thus, each node, v_i, also acts as a router within the network. When node v_i receives a message, it examines the message destination pseudonym. If v_i is the intended destination, then the node keeps and processes the message. Otherwise, node v_i looks up the destination in the routing table in order to determine to which neighbor to forward the packet. Then, it re-encrypts the data for the next hop, replaces the network address (e.g., IP address) associated with the data with its own network address, and forwards the data to the next neighbor along the route to the destination.

Some overlay networks, most prominently Tor [16], use source routing, where the route to the destination is determined in a separate topology step, and is then included as part of the message. No local routing tables need to be maintained. This form of source routing is naturally detrimental to membership concealment, as much of the global topology information (the source routes) is now available at all nodes in the network.

In the following, we will briefly summarize routing algorithms that are topologically agnostic, that is, they can successfully route in any CCN topology.

8.1.1 Shortest Path Routing

Shortest path routing is a basic approach to routing with several different algorithms that are widely used. These algorithms are easily adapted for use within a CCN. As the name suggests, the shortest path routing algorithm attempts to determine how to go from the source node to the destination node in the fewest hops, the shortest geographic distance, or the fastest path as possible. Two popular shortest path routing algorithms are the *link-state routing algorithm* and the *distance-vector routing algorithm*. These routing algorithms are well studied and easily ported to a CCN.

In the link-state algorithm, each node talks to all other nodes within the network providing them with the latency costs from it to its connected neighbors. The node passes a separate entry for each neighbor consisting of its logical address, the neighbor's logical address and the latency estimate between the two. Each node can then use this information to build up and update its routing tables, determining the path with the lowest latency path to each node based on the accumulated estimates that it receives from all other nodes. Membership concealment is preserved because, though each node uses network addresses to communicate with its neighbors in determining latency, the network addresses are not shared. Instead, the logical addresses are used to communicate the routing table updates.

In the distance-vector algorithm, each node talks only to its connected neighbors providing least-cost estimates from itself to all other known nodes in the network. Similar to the link-state algorithm, the distance-vector algorithm communicates the destination of each latency estimate by its pseudonym. The distance-vector algorithm has less computational complexity and message overhead since each node is sharing latency estimates only with its neighbors. However, it suffers from the *count-to-infinity* problem, which is the slow recognition of the network to realize when a node becomes unavailable for routing. There are solutions to the count-to-infinity problem, but it requires additional complexity in the routing algorithm. On the other hand, the link-state algorithm does not have the count-to-infinity problem, but does require significantly more traffic to maintain, creating a more detectable signature.

8.1.2 Routing by Selective Flooding

Selective flooding provides routing without the need for maintaining routing tables. A node would simply forward a packet to all neighboring nodes, except the one from which it received the message. This approach, however, would require a mechanism to prevent messages from being forwarded forever. A *time-to-live* field could be added to the packet. The value in this field would be decremented at each intermediate node until it reached zero, at which point the packet would no longer be forwarded. Another option is to buffer forwarded packets for some period of time such that those with duplicate payloads are not forwarded. However, flooding also raises the signature of the network and may allow it to stand out more easily against the other network traffic, thus making it more easily detected. Furthermore, since packets are re-encrypted for each hop, flooding is very computationally expensive.

Selective flooding could also be used in a more limited way to update routing tables. In this case, we assume that the fastest route in the network from Alice to Bob is also the fastest route from Bob to Alice. Periodically, Alice initiates a message and sends it to each direct neighbor. Each neighbor, in turn, forwards the packet to all direct neighbors, except Alice. This continues propagating the message throughout the network, which will eventually reach Bob, who forwards the message on in a similar manner. Bob updates his routing table by associating Alice's pseudonym with the neighbor from which he first received the message. Then, Bob will send all subsequent received messages destined for Alice through that same neighbor. With this approach, each node maps the pseudonym of all other nodes in the network to one of their neighbors. Membership concealment is, thus, maintained by controlling the network promiscuity of each node.

8.2 Routing in Deterministic Topologies

For routing in deterministic topologies, we assume that each node knows the number of nodes in the network. We will show how, from this information, each node can make local routing decisions. Knowing the number of nodes in the network, each node can in fact construct a model of the CCN topology. With this model in memory, each node, v_i, can determine the route from v_i to a destination node, v_d.

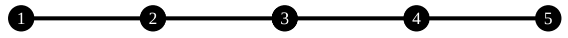


Figure 8.1: Path topology on 5 nodes, P_5

Routing in the *linear* topology (see Figure 8.1) is simple. For any node on the network that receives a message, it checks the destination pseudonym to see if it is the intended recipient. If it is, the node keeps the messages. Otherwise, it simply forwards the data to the next node in the chain, i.e., the node from which it did NOT receive the message.

Often more complex deterministic topologies, we can take advantage of the particular structure of the topology in order to make efficient local routing decisions. In Section 5, we described the Extended Gunther-Hartnell construction and the Extended Robertson construction. In the following sections, we describe such routing algorithms for these two topology constructions.

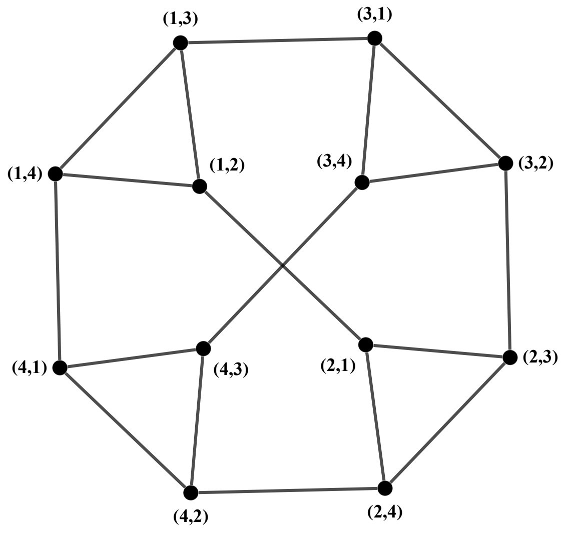


Figure 8.2: Gunther-Hartnell topology on 12 nodes (Cl_3)

8.2.1 Routing in Gunther-Hartnell Topologies

In Gunther-Hartnell topologies (described in Section 5), we can reduce the routing to a constant time complexity. This is accomplished by assigning logical addresses that serve as pseudonyms within the overlay topology. A logical address of a node in a Gunther-Hartnell network consists of a pair of numbers, $(x, y) \in \mathbb{N}^2$, where

x represents the number of the clique that contains v_i, and y represents the node number of v_i within the clique. Figure 8.2 shows a Gunther-Hartnell graph with four cliques of three nodes each. Node $(2, 4)$ in this graph is node number four in clique number two. Note that Clique x does not have a node with number x; that is, there are no nodes with logical address (x, x). Node v_i, with the logical address (x, y), will be neighbors with all other nodes in the same Clique x. Each node in Clique x has the logical address (x, z_j), where $z_j \in \mathbb{N}$ represents the node number of v_j within the clique, and $z_j \neq x$. Node v_i is also a neighbor to Node v_k, where v_k has the pseudonym (y, x), that is node number x in clique number y.

The maximum number of hops between any two nodes in a GH topology is three (one hop in the source node's clique, one hop to the destination node's clique, and a third hop in the destination node's clique). Thus, when node v_i receives a message, the destination pseudonym can be only one of four cases. Algorithm 8.3 describes a node's selection process for the next hop along the route when it receives a packet to route to the node with address (r, s).

Algorithm GH Routing as described in Figure 8.3 applies for fully populated GH topologies. For GH topologies with an arbitrary number of nodes, that is, GH topologies with nodes missing, this algorithm fails to work correctly. Node v_i may not be connected to an external clique because Node v_k with logical address (y, x) may not exist. The way GH graphs are constructed and grow allows for a modification of Algorithm GH Routing to handle partially populated GH graphs as well.

The GH construction adds a new node to each existing clique before starting a new clique. Figure 8.4 shows a GH topology on three cliques with two nodes each. Then, a new node is added to each clique before the forth clique is started. Thus, if the node with the logical address of $(3, 4)$ needed to route a message to clique 4, it could not do it directly (as per Algorithm GH Routing) because the node with

Algorithm **GH Routing :**

Input: Current node with address (x, y) and destination node with address (r, s).

Output: Next hop along the shortest route or *null* to indicate termination.

Step 1: If $x \neq r$ and $x \neq s$, then destination is in an unrelated clique; return (x, r).

Step 2: If $r = y$, then destination is in the neighboring clique; return (y, x).

Step 3: If $r = x$ and $s \neq y$, then the destination is a neighbor; return (x, s).

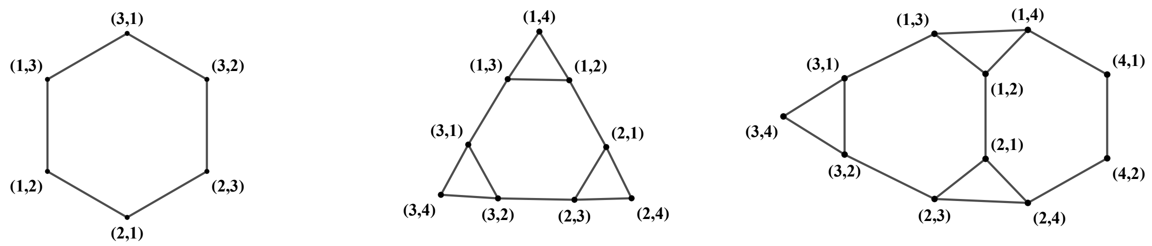
Step 4: If $(x, y) = (r, s)$ then the destination is reached; return *null.*

Figure 8.3: Routing in a Gunther-Hartnell topology.

address $(4, 3)$ does not exist. Instead, the message needs to be routed to either Clique 1 or Clique 2, since these are the only cliques that can reach Clique 4 from Clique 3. This can be predicted locally by the node at $(3, 4)$ and an alternate route can be chosen. This adds, at most, two more hops to the route.

8.2.2 Routing in Extended Robertson Construction Topologies

In Section 5 we described the Extended Robertson construction. Topologies were generated with this construction by forming cycles of order $p \in \mathbb{N}$, where p is prime. The cycles are then connected to each other according to the generated offset matrix, which specifies which p-gram should connect to which p-gon and the associated offset between the cycles. A logical address to each node in this topology consists of the triplet (x, y, z), where $x \in \mathbb{N}$ denotes the cycle pair, $y \in \{0, 1\}$ denotes whether the cycle is a p-gram or a p-gon, and $1 \geq z \geq p$ denotes the node number within the



(a) Cl_2.   (b) Cl_2 + 3 nodes.   (c) CL_3 − 1 node.

Figure 8.4: Growth of a GH topology

cycle.

Let (r, s, t) be the logical address of the destination node. When node v_i receives a message, the destination logical address can be one of five cases:

1. In the first case, the destination cycle pair $r \neq x$, and v_i must forward the message. If v_i is not directly connected to the r cycle then v_i forwards the packet to the closest known cycle–if $r > x$ then v_i forwards it to the neighbor with the largest cycle pair, otherwise v_i forwards it to the smallest known cycle pair.

2. In the second case, v_i does have a neighbor with cycle pair r and forwards the packet accordingly.

3. In the third case, $r = x$, so v_i examines s. Each p-gon is connected to a p-gram, both of which are in the same cycle pair. Thus, if $s \neq y$, then v_i forwards the message to the neighbor with which it shares a cycle pair.

4. In the fourth case, $r = x$ and $s = y$. Therefore, the message is in the correct cycle. If $t = z$, then v_i is the recipient of the message.

Algorithm **Extended Robertson Routing :**

Input: Current node with address (x, y, z); destination node with address (r, s, t); and offset matrix h with entries, a_{ij}

Output: Next hop along the shortest route or *null* to indicate termination.

Step 1: If $x \neq r$ and $a_{xr} = -1$, then the destination is not in a neighboring cycle pair; if $r > n$, return $(r, \neg y, (z + a_{xm})(mod\ p))$, where $m = \max\{i\ :\ a_{xi} \geq 0\}$; otherwise, if $r < n$, return $(r, \neg y, (z + a_{xm})(mod\ p))$, where $m = \min\{i\ :\ a_{xi} \geq 0\}$;

Step 2: If $x \neq r$ and $a_{xr} \geq 0$, then the destination is in a neighboring cycle pair; return $(r, \neg y, (z + a_{xr})(mod\ p))$.

Step 3: If $r = x$ and $s \neq y$, then destination is in the correct cycle pair but the wrong cycle; return $(x, \neg y, (z + a_{xx})(mod\ p))$.

Step 4: If $r = x$, $s = y$, and $t \neq z$, then the destination is in the same cycle, so route around the cycle; return $(x, y, (z + 1)(mod\ p))$.

Step 5: If $(x, y, z) = (r, s, y)$ then the destination is reached; return *null*.

Figure 8.5: Routing in an Extended Robertson topology.

5. Otherwise in the fifth case, v_i forwards it to the neighbor node within the same cycle that is closest to the destination (i.e., either $z + 1$ or $z - 1$, both $mod\ p$).

Algorithm GH Routing is shown in Figure 8.5.

Unlike Gunther-Hartnell topologies, the Extended Robertson construction produces path lengths that grow unbounded as the number of nodes increase. If the message is in the correct cycle, then $\lfloor p/2 \rfloor$ hops are needed in the worst-case to reach the destination. If the message is in the correct cycle pair but the wrong cycle, then

1 hop will get it to the correct cycle. If the message is not in the correct cycle pair, then the number of hops is dependent on the number of nodes in the network as $\lceil (n-50)/40 \rceil + 1$.

Thus, in an Extended Robertson construction topology with n nodes and cycle size p, in the worst-case, the number of hops required for routing will be:

$$\left\lceil \frac{n-50}{40} \right\rceil + \left\lfloor \frac{p}{2} \right\rfloor + 2 \quad . \tag{8.1}$$

This gives a linear time complexity for routing in an Extended Robertson construction topology.

It will often be the case where the last cycle pair within the construction is incomplete. In these cases, the routing algorithm in Figure 8.5 may fail if the last hop along the expected path does not exist. However, assuming that each node knows the actual size of the network, the benefit of deterministic topologies such as the Extended Robertson construction is that each node can locally construct a model of the network topology; then, with a little more complexity in steps 2, 3 and 4 in the routing algorithm, anticipate routing failures and adjust the routing path along existing nodes.

8.3 Deadlocks and Circular Routing

One common difficulty in efficient routing in deterministic networks is the need to avoid deadlocks and circular routing. Deadlocks can occur in the Gunther-Hartnell and Extended Robertson construction routing algorithms when the neighbor returned by the algorithm has failed. As presented, the algorithms assume that all nodes within the network are operational. In order to circumvent this problem, additional algorithmic complexity is needed to identify failed neighbors and advertise to other nodes that the failed neighbor is unreachable.

Circular routing would only occur in the case where a new node has joined the network but not all nodes have been notified yet so that they update their internal model. Thus, if Node v_i with the updated view of the network routes to Node v_j, but Node v_j has not been updated and expects to route through Node v_i then, unless either node recognizes that returned packets, the two nodes will pass the packet back and forth until Node v_j is updated. However, the problem would occur on the border between the neighboring updated node and the non-updated node. Thus, the update would be passed to v_j and then the packet returned. The update would then proceed the packet and fan out into the network. The misrouted packet would then be routed according to the new network configuration from its current location to the destination.

8.4 Conclusions

Deterministic topologies with relatively high subversion impedance, such as the Gunther-Hartnell and Extended Robertson constructions, offer an internal structure that facilitates efficient routing. We have shown that for the Gunther-Hartnell and Extended Robertson constructions routing schemes with local routing decisions exist. Even when topologies are not complete, that is, some nodes are missing, these routing schemes remain effective (after some minor modifications) provided that: (a) all nodes know the number of nodes in the system, and (b) the way the network grows when nodes are added follows a given pattern, which we described.

Other deterministic topologies with very efficient routing algorithms, for example hypercubes and bit-flipping-based routing, can be amenable to routing for incomplete topologies [33]. While the Gunther-Hartnell and Extended Robertson constructions routing algorithms can handle incompletely populated topologies, they assume that all joined nodes in the network are functional. When arbitrary nodes fail, the routing can not adapt. To handle arbitrary node failures, one would need to borrow techniques from common network routing protocols, which can be easily ported to CCNs and offer more flexible routing at the expense of a higher network signature, either through redundancy of message traffic or traffic needed to maintain routing tables. In either case, routing can be done in a way that preserves the anonymity, membership concealment and resiliency of CCNs.

9. IMPLEMENTATION AND RESULTS

We implement a prototype CCN using a traditional overlay network design approach, where the transport layer or higher layers of the underlying network are used to carry the link-layer functionality of the overlay. In order to allow for link-layer diversity in the overlay, the CCN architecture uses multiple channels, one for each type of link-layer connection. As we will describe below, this allows CCN links to be established over multiple different protocols in the underlying networks. Our implementation also allows for both the plug-and-play of new types of channels and new types of applications.

Figure 9.1 shows the basic architectural layers of a CCN node in accordance with our extension of the protocol stack. At the top of the stack is the application. The application at the source node communicates with the application at the destination node. It does this by passing a message to the CCN transport layer. The CCN transport layer converts the message into one or more packets, encrypts these packets and passes them to the anonymity preserving layer. The anonymity preserving layer handles routing, and thus, properly addresses each packet before sending the packet down to the channel manager. The channel manager checks the single-hop destination of the packet, encrypts its data accordingly and then passes the packet to the appropriate channel. The channel forwards the traffic to the next node along the route.

Received messages are passed up the protocol stack in a similar manner. The channel receives the data from the network and creates a new packet. The packet is sent to the packet manager where it is decrypted and passed to the anonymity preserving layer. The anonymity preserving layer checks the destination. If the

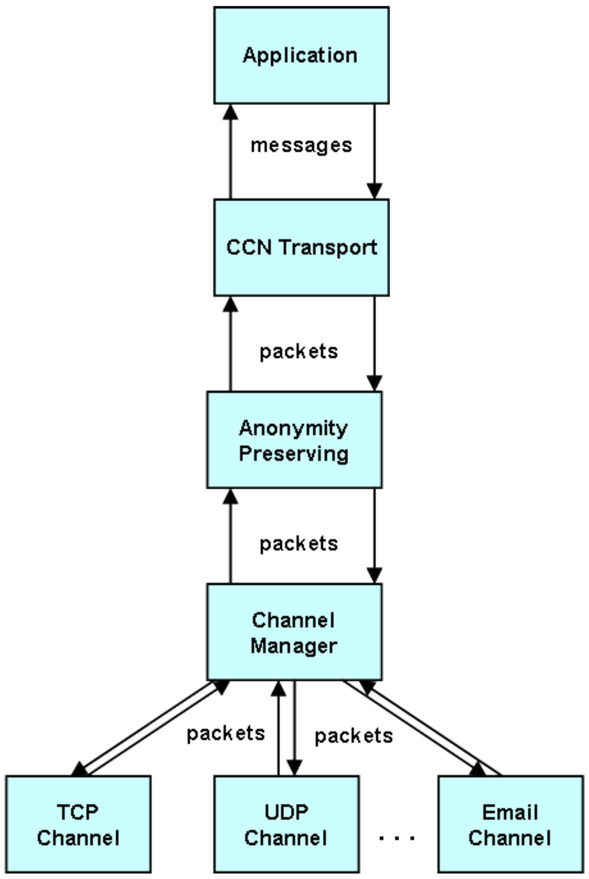


Figure 9.1: CCN architecture

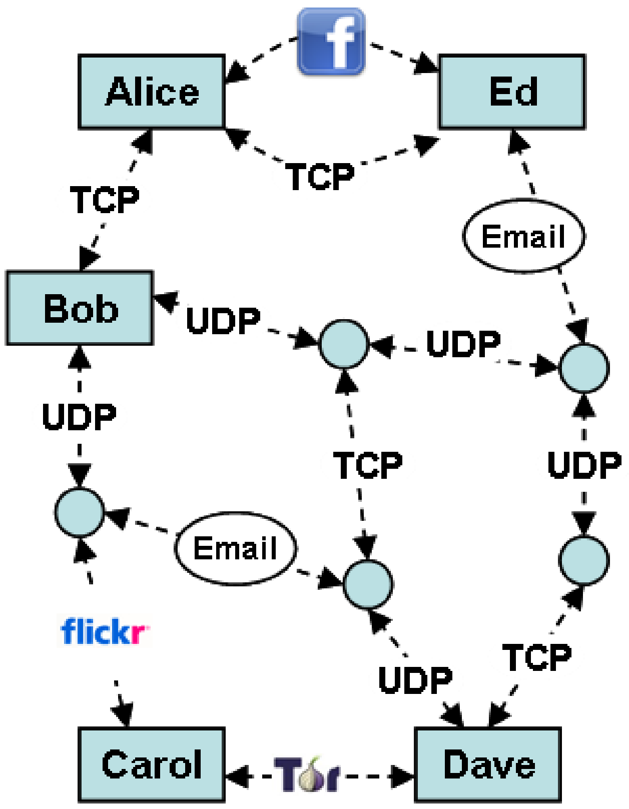


Figure 9.2: Example CCN

traffic is intended for the node, the packet is sent up to the CCN transport layer. Otherwise, it is readdressed and sent back down. At the destination node, the CCN transport layer decrypts packets and converts them to messages. The application pulls messages from the transport layer as they become available.

We now address each of these layers in more detail.

9.1 The Channel Layer

In the Internet protocol suite, the *link layer* is responsible for achieving reliable, efficient communication between two adjacent machines; that is, machines that are physically connected by a communication channel that acts conceptually like a wire [58]. Though they are topological neighbors, the path between Alice and Bob in

Figure 9.2 consists of multiple hops between devices, including switches, routers, firewalls, etc. As the link layer is responsible for communications at each of these hops, within a CCN, the *channel layer* provides communication between topological neighbors and provides the services within the overlay network that the link layer provides to the underlying network. The channel layer consists of one or more *channels* that pass data between adjacent nodes.

The channel layer provides single-hop communication within the overlay network. Each channel will have different performance characteristics in support of the communications requirements of the group. In our implementation, one channel utilizes *user datagram protocol* (UDP) to provide low latency support for near-real-time communication at the expense of an increased risk of detectability, and *transmission control protocol* (TCP) to provide additional protection against dropped packets at the expense of increased latency. A third channel implements the functionality of a mix [9] providing high level resilience against attacks that attempt to undermine anonymity. Additional channels can be easily developed based on the particular requirements of the group.

Thus, Alice can send data to Bob in a variety of ways. The type of channel used is dependent on the type of service needed at the higher levels. Each type of channel offers trade-offs between performance and anonymity. Low latency communication provides near-real-time communication for group members at the risk of providing an adversary with timing signatures for tracing packets across the overlay network, thus undermining anonymity. If near-real-time communication is not required, then nodes can both batch messages and introduce variations in timing to obscure communication signatures and increase anonymity. We assume that the channels used by the network are agreed upon by the participants and instantiated at each node.

9.1.1 TCP Channel

The most straightforward channels to implement are based on UDP and TCP. These common types of connections address the relevant reliability issues that need to be dealt with at the channel layer. In a standard network, we think of the media access control (MAC) address as the link layer address. However, in the overlay topology of a CCN, an IP address would act as a CCN channel layer address. In both the UDP and TCP channels, the channel maintains a table of the IP address and ports of trusted neighbors. Data received from an unknown IP address is discarded.

TCP provides a reliable transmission of data between adjacent nodes. TCP supports acknowledged connection-oriented service between adjacent nodes. In a CCN, a TCP Channel instantiates two sockets to each of its neighbors: one socket is for sending data; and another socket is for receiving data. We implement TCP as an asynchronous socket server on each node. This allows the node to handle connections from multiple neighbors simultaneously. When data needs to be sent on the TCP channel to a particular neighbor, the channel checks to see if a socket exists for sending. If not, it connects to the TCP server of the neighbor and a thread is spawned on each node to manage the communications on this socket. Thus, a single socket can be used repeatedly for communication between nodes, thus, minimizing the overhead of the three-way handshake needed to set-up a TCP connection. Since a node only communicates at the channel level with its topological neighbors, only a relatively small number of sockets need to be maintained.

The TCP channel will ensure that a packet payload arrives across a single hop in order and without data loss. However, it makes no guarantees that the end-to-end traffic will arrive in order and without data loss. End-to-end packet ordering and data loss is handled by the CCN transport layer.

9.1.2 UDP Channel

UDP provides only a basic communication service between nodes. The delivery guarantees provided by TCP are not provided by UDP. Under UDP, *datagrams* are sent from one node to another with no expectation for an acknowledgment and no timeout. However, UDP is important in situations when low latency is more importance than data loss.

UDP offers unacknowledged connectionless service between adjacent nodes in a straightforward manner. It can be modified easily for acknowledged connectionless service. Though it may affect performance, acknowledgment can always be handled at higher layers between the source node and destination node.

9.1.3 Remailer Channel

Traditional mix networks provide anonymity by sending messages through a series of email servers, each of which replace the source header information with its own to delink the source from the destination; wait some random period of time before resending to prevent timing correlation attacks; and batch multiple messages together to prevent message identification by message size [9, 14, 25]. This is easily integrated into our system at the channel layer.

To facilitate this channel, each node registers a disposable email address (e.g., gmail) to which their neighbors could send or forward email. Similar to most email clients, the channel checks this email account periodically and processes any received email. The channel maintains a table of trusted neighbors identified by their IP address and email address. Emails from non-neighbors are discarded. A received email is debatched, if necessary, into separate payloads and a packet is generated for separate payload.

Packets to be sent are stored in a buffer for a short period of time. This disrupts the timing of the traffic and allows the node to collect email from multiple neighbors. Periodically, packets destined to the same neighbor are batched appropriately and sent as an email to the email address of the appropriate neighbor.

9.2 Channel Manager Layer

The *channel manager* is responsible for instantiating and monitoring all channels used by the node and for hop-level encryption and decryption. Thus, the channel manager will start and gracefully shutdown each channel, as necessary; decrypt data it receives from any channel; encrypt data being sent to a neighbor; and pass data between the anonymity preserving layer and the appropriate channel.

The channel manager has an asymmetric key pair which it uses for decryption of the data it receives from a channel. It also maintains a table of public keys for all trusted neighbors. When data is to be sent or forwarded to a neighbor, the channel manager uses the appropriate key. For some communication, the channel manager can negotiate symmetric keys for follow-on communications, i.e., TLS. Each symmetric key is used to encrypt and decrypt traffic with a single neighbor. Periodically, the node or its neighbor will negotiate a new symmetric key.

Once received data is decrypted, its packet is passed to the anonymity preserving layer. Likewise, once data to be sent is encrypted, the packet is passed to the appropriate channel.

9.3 The Membership Concealing Layer

The *membership concealing layer* is responsible for determining how packets are routed from source to destination. This layer is analogous to the *network layer* in the Internet protocol suite. In a CCN, the anonymity preserving layer is responsible for maintaining a routing table that associates node pseudonyms with a neighbor network address. This layer also provides a level of security.

For example, in Figure 9.2, if Alice wants to communicate with Dave, her message must route through both Bob and Carol. The anonymity preserving layer is responsible for determining to which neighbor the packet needs to be sent in order for it to reach its destination.

9.3.1 Anonymity Preserving Routing

The anonymity preserving layer of a node examines the destination logical address of an arriving message. If the given node is the destination, then the packet is passed to the transport layer. If not, then the node determines to which neighbor to route the packet. Then, it passes the updated packet to the channel manager layer for encryption and transmission.

9.3.2 Single-hop Security

The anonymity preserving layer is the appropriate layer for implementing security protocols that validate singe-hop traffic. For example, a simple approach might be to check the single-hop time-stamp of the data packet and reject it if the time stamp is outside some reasonable window of expected transmission latency. This approach would protect against replay attacks by an adversary.

Also, if routing by selective flooding is used, though the end-to-end data cannot be read, this layer can compare the data it receives from one neighbor against the data it receives from its other neighbors to detect attempts made by an adversary at watermarking. Each node would receive the same packet multiple times from different, independent routes. Any discrepancy between the packet copies could indicate an attempt by an adversary to tamper with message traffic. More complex approaches could be based on this approach allowing neighbors to act cooperatively to detect subversions.

9.4 The Transport Layer

The *transport layer* is responsible for packet creation, packet buffering, packet ordering and end-to-end cryptography. The transport layer receives a message from the application layer and breaks it down into one or more packets based on the desired packet size relative to the message size. These packets are ordered by sequence numbers and sent to the destination transport layer.

The destination transport layer buffer stores packets that are passed from the anonymity preserving layer until the application layer is ready for them. Because many channels are asynchronous or unreliable, packets may arrive out of sequence. Sequence numbers are used to preserve ordering. Packets are inserted into the buffer based on their sequence number. The starting sequence number and ending sequence number provide a means of synchronizing the end-to-end session and requesting lost portions of data. Coupled with the source field and application identifier, it also allows for separate buffering for different applications and different sessions. If all packets are received, the set of packets is converted into a single message and buffered until retrieved by the application.

The same cryptographic functionality provided at the channel manager layer for single-hop communication is provided for end-to-end communication at the transport layer. Asymmetric encryption is used for high latency communication and negotiation of symmetric keys for low latency communication.

The transport layer can also take steps to assess the validity of received traffic. The additional packet information provided by the source node can be used to detect subversions that were missed at the routing layer.

9.5 The Application Layer

The *application layer* contains a variety of protocols that are commonly needed, such as file transfer and various other general and special-purpose facilities. The plug-and-play design of the architecture allows for the development of additional applications, as needed.

9.5.1 File Sharing

The heart of most all applications within a CCN is file sharing. The application divides up the file into a set of messages and each message is passed to the CCN transport layer. Files could be any other type of data, including text, voice, or image based. The anonymity, latency and delivery guarantees required by file-sharing are dependent on the needs of the user.

9.5.2 VoIP and VTC

VoIP and VTC require low latency between the source and destination nodes. The CCN topology, of course, adds latency because it extends the hop distance from the source to the destination by routing the traffic through a series of intermediate nodes. This restricts the channel layer services to those that minimize latency. These types of services increase the risk of undermining sender-receiver unlinkability.

VTC is especially data heavy and, thus, creates a significant signature. Though routing by flooding would propagate traffic from the source to the destination along the fastest route, it would require significant bandwidth and could create serious congestion issues. More importantly, the signature created by flooding video traffic could be very distinguishable from the background Internet traffic and significantly undermine membership concealment.

9.5.3 Electronic Mail

In our implementation, we have a channel that pulls and forwards packet data from email accounts associated with legitimate neighbors. This type of channel is high latency, but allows for the batching of multiple data packets. These two features provide high resilience against attacks attempting to undermine the anonymity of the network. A simple CCN email application would serve as a client that would pass message traffic to and from the email channel.

9.5.4 Web Browsing

Risk to membership concealment increases if a node allows traffic to "exit" the network (e.g., a Tor exit node). Exit nodes are susceptible to identification by honey pot web sites run by adversaries. Use of a CCN to access public web sites incur an increased level of risk and must be used cautiously.

However, assume that a CCN node is running an application that passes traffic to and from a web proxy. Then, network participants using an Internet browser connecting to an application on their own node could surf anonymously in a way that localizes the risk of compromise to a single node.

Another approach is if one or more nodes in the network run web servers that are accessible by other network members. The web server would only accept traffic from adjacent nodes. These adjacent nodes only accept traffic from their neighbors, and so forth. Thus, traffic to the web server is restricted to members of the network.

9.6 A Test Application

In order to test our architecture, we developed an application that would communicate with an Internet browser and another that would communicate with a web proxy. Figure 9.3 shows the structure of the network. In this set-up, the participant,

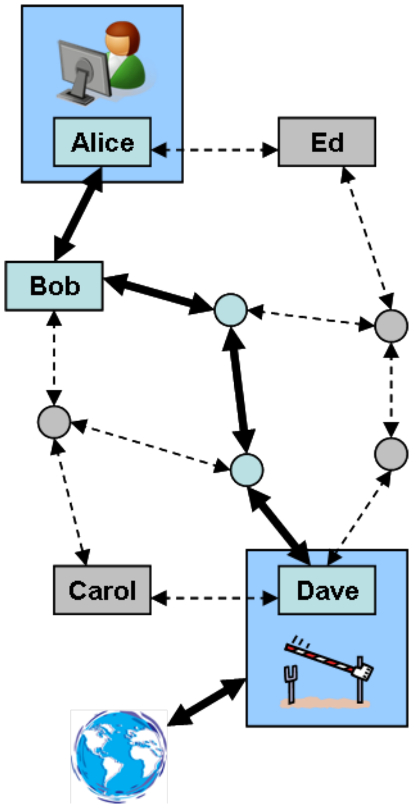


Figure 9.3: Example application

Alice, runs a common commercial Internet browser configured to communicate with a CCN node. On a different machine, Dave is running a simple commercial web proxy configured to listen for connections on that computer's loopback address and a specified port. Alice uses the browser to send HTTP requests through the CCN, and Dave, upon receipt, forwards the traffic to the web proxy. The web proxy, then, forwards the traffic to the requested web server and forwards the response back to the CCN. The response is routed through the CCN from Dave back to Alice and to her browser which then renders the response appropriately.

9.6.1 Connecting to the Browser

The application on Alice's node is a simple TCP server listening to a TCP socket at the loopback address of the computer and a specified port. The Internet browser is configured to send traffic to a web proxy; in this case, the loopback address and port monitored by the CCN node. The browser is, then, used as normal. However, it connects and sends the HTTP traffic to the loopback address where it is received by Alice's CCN application. So, in Alice's browser, a URL is entered and the browser generates the HTTP GET request which is sent via a TCP socket to Alice's CCN application. From there, the application converts the traffic to a message and sends the message to the CCN transport layer. The CCN transport layer converts the message to one or more packets and sends each to the appropriate neighbor.

9.6.2 Connecting to the Proxy

Dave's application connects to the web proxy via a TCP connection and forwards Alice's HTTP request. When the application receives the response from the web, sent from the proxy, it performs the same as Alice's application. It converts the response to a message and forwards the message to its own CCN transport layer where the traffic is sent on its return journey through the CCN back to Alice.

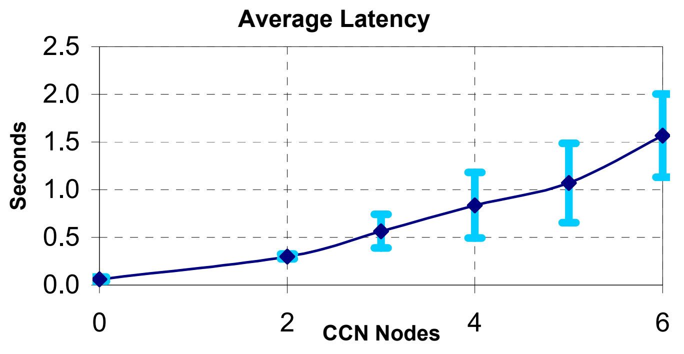


Figure 9.4: Network latency relative to number of CCN nodes used (CI = 95%).

9.6.3 The Intermediate Nodes

The traffic is then routed through zero or more intermediate CCN nodes before it arrives at Alice's CCN node. Each of the other machines on the network is running a CCN node with the only differences between nodes are the neighbors to which they are connected.

9.6.4 Results

We tested our network over a public subnet. HTTP relies on TCP due to its relatively low latency and reliable, ordered delivery. Though intermediate nodes could communicate via UDP, the lack of reliable delivery is problematic for our application. Thus, during this test, we restricted all channels to TCP.

We first established a baseline for the latency between the browser on Alice's computer, the proxy on Dave's computer, and the web site used. Then, we tested the latency using a CCN of only two nodes, Alice and Dave. From there, we continually increased the size of the network by one, testing the latency for each. The longest the route that we tested consisted of six CCN nodes.

Figure 9.4 shows the average latency (with a confidence interval of 95%) required to send an HTTP get request of 1023 bytes and receive the response of 47,024 bytes.

The baseline gives an average time of 0.06 seconds. Routing the traffic through a CCN with two nodes increases the average latency to 0.30 seconds. The longest route we tested involved six CCN nodes. The average latency in this case was 1.57 seconds.

We would see the highest latency during the first trial of each test. On a CCN of two nodes, the latency on the first trial was 0.60 seconds higher than average, and on a CCN of six nodes, the latency was 1.10 seconds higher than average. During the first trial, each node is establishing TCP connections via the three-way handshake with neighbors along the route. Once these connections were established, they are maintained for the second and subsequent trials, resulting in a much lower latency.

9.7 Conclusions

In the previous sections, we described the architecture for our prototype implementation of a covert communication network. By definition, trust entails a component of risk. In some circumstances, use of a covert communication network is a life-and-death decision. Thus, the network should not induce more risk than absolutely necessary. Covert communications networks attempt to minimize this risk while providing participants with a resilient communications network. This type of network is promising for high risk situations.

As previously isolated groups become connected via the Internet and gain access to information and ideas deemed subversive by their authorities, CCNs will become an important tool in the fight against censorship. Even more liberal societies are seeing government attempts at information control. Ultimately, CCNs can help bring freedom of speech to those who have never had it and guard it for those that are seeing it threatened.

10. CONCLUSIONS

In this dissertation, we have presented the motivation and requirements for covert communication networks. As we defined in Section 1, we identify the need for the ability to communicate in a way that ensures (a) confidentiality and anonymity of the communication; (b) concealment of participation in the network to both other members of the group and external eavesdroppers; and (c) resilience against disconnection. As a possible solution we propose covert communication networks, which are architected as overlay, peer-to-peer (P2P) networks over existing communication infrastructures. We rely on standard methods of cryptography to provide confidentiality, draw on techniques from mix-style networks for anonymity, and extend the application of membership-concealing overlay networks in order to protect the identity of network participants while providing resiliency against network partitioning.

We described the requirements of a CCN and the trade-offs between high-latency and low-latency communication within such a network. We discussed the mechanisms for confidential and anonymous communication and examined the trade-offs between node survivability and network connectivity and described various single-hop channel implementations.

In order to measure topologies for suitability of use in covert communication networks, we defined several measures based on what we call subversion impedance. Subversion impedance quantifies the balance in a topology between membership concealment and resilience. By determining the subversion impedance in the worst case and the average case, we can assess the risk to participants associated with a particular network overlay topology. Using these measures, we identified two constructions (the Extended Robertson construction and the Extended Gunther-Hartnell construction) that allow the network to grow as new nodes join and which generate topologies with near-optimal subversion impedance regardless of the number of nodes.

We also defined measures of subversion impedance for assessing families of random graph topologies and used these measures to analyze Erdös-Rényi (ER) and Barabási-Albert (BA) random graphs. We learned that, for the range of graphs examined, ER graphs have higher expected local subversion impedance than BA graphs. Furthermore, the expected global subversion impedance of BA graphs is very low with the connectivity rarely surviving the removal of the worst-case neighborhood. Additionally in $G_{n,p}$ graphs, we found a good closed-form estimate for both the expected connectivity using order statistics and the expected local subversion impedance.

Given the need to preserve membership concealment, membership management is especially difficult in a covert communication network. As such, we developed algorithms for joining a covert communication network. These algorithms protect against unnecessary exposure of network addresses while allowing new nodes to increase their connectivity for resilience. We discussed approaches for dealing with node departure and described approaches to healing damage to the topology to retain high subversion impedance.

We discussed general approaches to routing that are easily ported for use in covert communication networks and developed efficient routing protocols in support of the Extended Robertson construction and the Extended Gunther-Hartnell construction.

Incorporating the ideas above, we designed, built, and tested a prototype system for instantiating a CCN. We described the system architecture and design choice reasoning. This system supports high- and low-latency channels, single-hop and end-to-end routing. It also encapsulates topology management and associated protocols and provides a proof-of-concept interface for use with both off-the-shelf and custom applications.

As network communication becomes more and more ubiquitous, applications need to keep pace that will protect both the communication and the communicators. It is our hope that the work described here is a meaningful contribution to the field of network privacy and is of benefit to those on the front lines in the fight against oppression and tyranny.

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APPENDIX A

GRAPH THEORY TERMS AND NOTATION

We model the covert communication network by a *graph* $G = (V, E)$ with *nodes*, V, representing the members and the *edges*, E, representing the neighbor relation between members. We refer to the number of nodes in G as its *order* and denote it by $|G|$. The *size* of G is the number of edges in G denoted by $||G||$. G is *connected* if any two nodes are linked by a path in G. The neighborhood (or open neighborhood) of a node v, denoted by $N(v)$, is the set of nodes adjacent to v. The *closed neighborhood* of a node v, denoted by $N[v]$, is simply the set $\{v\} \cup N(v)$. Given a graph G and a node $v \in V$, we let $H(G, v) = G - N[v]$ denote the *survivor graph* obtained by removing $N[v]$ and all edges incident with $N[v]$ from G.

A *component* of a graph G is a maximal connected subgraph of G. A connected graph G has a single component and an empty graph has no components. A graph that is not connected will have multiple components. Also, the order of the shortest cycle in G is said to be the *girth* of G, denoted by $girth(G)$.

A graph is *k-connected* if any two of its nodes can be joined by at least k independent paths. More formally, a graph G is called *k-connected* (for $k \in \mathbb{N}$) if $|G| > k$ and $G - X$ is connected for every set $X \subseteq V$ with $|X| < k$. The smallest integer k such that G is k-connected is the *connectivity*, $\kappa(G)$, of G. A *k-regular, k-connected* graph with $k > 0$ is connected and, thus, only has a single component.

The *degree* of a node v, denoted by $deg(v)$, is the number of edges at v. The number $\delta(G) = \min\{deg(v) \mid v \in V\}$ is the *minimum degree* of G, and the number $\Delta(G) = \max\{deg(v) \mid v \in V\}$ is the *maximum degree* of G. Naturally, if G is a connected graph of order n, then $1 \leq \kappa(G) \leq n - 1$, and for every graph, G,

$$\kappa(G) \leq \delta(G) \quad . \tag{A.1}$$

If all the nodes of G have the same degree k, then G is said to be *k-regular*. If graph G is *k-regular* and *k-connected*, then

$$\kappa(G) = \delta(G) = \Delta(G) \quad . \tag{A.2}$$

We refer the reader to Table A.1 for a summary of the graph theoretic notation used.

Table A.1: Table of symbols used.

$\mathbb{G}^n$	the set of all graphs of a given order, n
$G = (V, E)$	a graph with a set of nodes V and edges E; also denoted by G
$\|G\|$	the order of graph G
$\mathbb{G}^n$	the set of all graphs of order n
$N(v)$	the set of nodes adjacent to node v; its (open) neighborhood
$N[v]$	the closed neighborhood of v; $\{v\} \cup N(v)$
$\delta(G)$	the minimum node degree within graph G
$\Delta(G)$	the maximum node degree within graph G
$\kappa(G)$	the connectivity of G
$S(G, v)$	the secrecy measure of graph G and node v
$K(G, v)$	the resilience measure of graph G and node v
v^*	the node v that will result in the lowest measure of $S(G, v)K(G, v)$ for a given graph
$\gamma^*(G)$	the subversion impedance of a graph G; determined by $S(G, v^*)K(G, v^*)$
$H^*(G)$	the worst case survivor graph of G produced by removing the set of nodes $N[v^*]$ from G; $H^*(G) \equiv H(G, v^*)$
$\Gamma(n)$	the optimal subversion impedance; the highest $\gamma^*(G)$ of all graphs $G \in \mathbb{G}^n$