Security in Wireless Mesh Networks

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Chapter 1

Privacy Preservation in Wireless Mesh Network

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Multi-hop wireless mesh network (WMN) has attracted increasing attention and deployment as a low-cost approach to provide last-mile broadband Internet access. Privacy is a critical issue in WMN, as traffic of an end user is relayed via multiple wireless mesh routers. Due to the unique characteristics of WMN, the existing solutions for Internet are either ineffective at preserving privacy of WMN users, or will cause severe performance degradation.

In this chapter, we propose a light-weight privacy preserving solution aimed to achieve well-maintained balance between network performance and traffic privacy preservation. At the center of this solution is an information-theoretic metric called "traffic entropy", which quantifies the amount of information required to describe the traffic pattern and to charac-

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terize the performance of traffic privacy preservation. We further present a penalty-based shortest path routing algorithm that maximally preserves traffic privacy by minimizing the mutual information of "traffic entropy" observed at each individual relaying node, meanwhile controlling performance degradation within the acceptable region. Extensive simulation study proves the soundness of our solution and its resilience to cases when two malicious observers collude. [2]

1.1 Introduction

Recently, multi-hop wireless mesh network (WMN) has attracted increasing attention and deployment as a low-cost approach to provide last-mile broadband Internet access [2, 4, 5, 3]. In a WMN, each client accesses a stationary wireless mesh router. Multiple mesh routers communicate with one another to form a multi-hop wireless backbone that forwards user traffic to a few gateways connected to the Internet. Some perceived benefits of WMN include enhanced resilience against node failures and channel errors, high data rates, and low costs in deployment and maintenance. For such reasons, commercial WMNs are already deployed in some US cities (like Medford and Chaska). Even large cities are planning to deploy city-wide WMNs as well [1].

However, to further widen the deployment of WMN, and enable it as a competitive player in the market of broadband Internet access, privacy issue must be addressed. Privacy has been a major concern of Internet users [12]. It is a particularly critical issue in the context of WMN-based Internet access, where users' traffic is forwarded via multiple mesh routers. In a community mesh network, this means that the traffic of a residence can be observed by the mesh routers residing at its neighbors. Despite the necessity, limited research has been conducted towards privacy preservation in WMN.

This motivates us to investigate the privacy preserving mechanism in WMN. There are mainly two privacy issues – data confidentiality and traffic confidentiality.

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- *Data confidentiality.* It is obvious that data content reveals user privacy on what is communicated. Data confidentiality aims to protect the data content and prevent eavesdropping by intermediate mesh routers. Message encryption is a conventional approach for data confidentiality.

- *Traffic confidentiality.* Traffic information such as who the users are communicating with, when and how frequently they communicate, the amount and the pattern of traffic, also reveals critical privacy information. The broadcasting nature of wireless communication makes acquiring such information easy. In a WMN, attackers can conduct traffic analysis at mesh routers by simply listening to the channels to identify the "ups and downs" of target's traffic. While data confidentiality can be achieved via message encryption, it is much harder to preserve traffic confidentiality. In this chapter we focus on the user traffic confidentiality issue, and study the problem of traffic pattern concealment.

We aim at designing a light-weight privacy preserving mechanism for WMN which is able to balance the traffic analysis resistance and the bandwidth cost. Our mechanism makes use of the intrinsic redundancy of WMN, which is able to provide multiple paths for data delivery. By intuition, if the traffic from the source (*i.e.*, gateway) to the destination (*i.e.*, mesh router) is split to many paths, then all the relaying nodes [3] along the paths could only observe a portion of the entire traffic. Moreover, if the traffic is split in a random way both spatially and temporally, then an intermediate node has limited knowledge to figure out the overall traffic pattern. Thus the traffic pattern is concealed.

Based on this intuition, we seek a routing scheme which routes data such that the statistical distributions of the traffic observed at intermediate relaying nodes are independent from the actual traffic from the source to the destination. To achieve this goal, we first define an information-theoretic metric – "*traffic entropy*", which quantifies the amount of information required to describe the traffic pattern. Then we present a penalty-based routing algorithm, which aims to minimize the mutual information of "traffic entropy" observed at each relaying node, meanwhile controlling the network performance degradation under the acceptable level.

[3] In this paper, we use the following terms interchangeably: wireless mesh router, intermediate relaying node, wireless node.

Considering the possibility of collusion, we evaluate our scheme under situation when two observers exchange their knowledge about the same destination. We measure this shared knowledge as "colluded traffic mutual information" and our simulation results show that our scheme is still viable in case of two colluding eavesdroppers.

The rest of this chapter is organized as follows. In Section 1.2, we present the overall architecture for privacy preservation in WMN. Section 1.3 and 1.4 focus on the traffic privacy issue. In particular, Section 1.3 presents the model to quantify the performance of traffic privacy preservation, and Section 1.4 presents the routing algorithm. The proposed privacy preserving solution is evaluated via extensive simulation study in Section 1.5. Section 1.6 discusses collusion problem possible with malicious traffic observers and its impact on our proposed scheme. Section 1.7 summarizes background knowledge and related work. Section 1.8 concludes the chapter and points out the future directions.

1.2 Privacy Preserving Architecture

We consider a multi-hop WMN shown in Fig. 1.1. In this network, client devices access a stationary wireless mesh router at its residence. Multiple mesh routers communicate with one another to form a multi-hop wireless backbone that forwards user traffic to the gateway which is connected to the Internet.

Two privacy aspects are considered in this architecture. *Data confidentiality* aims to protect the data content from eavesdropping by the intermediate mesh routers. *Traffic confidentiality* prevents the traffic analysis attack from the mesh routers, which aims at deducing the traffic information such as who the user is communicating with, the amount and the pattern of traffic. Our privacy preserving architecture aims to protect the privacy of each wireless mesh router, the basic routing unit in WMN. The architecture consists of the following functional components.

- *Key Distribution.* In this architecture, each mesh node, as well as the gateway, has a pair of public and private keys (KU, KR). The gateway maintains a directory of

certified public keys of all mesh nodes. And each mesh node has a copy of the public key of the gateway KU_g. The public key KU_i of mesh node i and KU_g are used to establish the shared secret session key KS_{gi}, which is used to encrypt the messages between them.

- *Message Encryption.* Let M be the IP packet sent from a source s in the Internet to a client d in the mesh network, and i be the mesh router of client d. The whole IP packet M, which contains the original source and destination address s and d, is encrypted at gateway g via the shared secret key KS_{gi}: $M_e = E(KS_{gi}, M)$. To route the encrypted packet M_e to its destination, the gateway prefixes the source route from the gateway g to the router i to the packet. The encapsulated packet is then forwarded by relaying routers in WMN. Likewise, packets traveled in the reversed direction are treated the same way. As the source address s and other higher layer header information, such as port, are all encrypted, the relaying routers are unable to obtain the information on who the client of router i is communicating with, and what type of application is involved. Since encryption and decryption take place only at the gateway and the destination mesh router, much less computation is required, which is a desired feature in WMN.

- *Routing Control.* With source route in clear text in an encapsulated packet, the intermediate mesh routers can still observe the amount and the pattern of the traffic of a particular mesh node i. To address this problem, our privacy preserving mechanism explores the path diversity of WMN, and forwards packets between the gateway and the mesh node via different routes. Thus any relaying router can only observe a portion of the whole traffic of this connection. In Section 1.4, we detail the design of a penalty-based routing algorithm, which randomly selects a route for each individual packet such that the observed traffic pattern at each relaying node is independent of the overall traffic. In our design, the gateway maintains a complete topology of the WMN, and computes the source routes between the destination mesh nodes and itself.

1.3 Privacy Modelling in WMN

1.3.1 Network Model

We model the WMN shown in Fig. 1.1 as a graph $G = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V}$ is the set of wireless nodes in WMN, and $\mathcal{E}$ is the set of wireless edges (x, y) between any two nodes x, y. Each node x maintains a logical connection with the gateway node g. Node x receives data from the Internet via g. The source and destination information of a packet is open to the relaying node. The traffic pattern of x can be categorized into two types: incoming traffic pattern and outgoing traffic pattern. In this paper, we mainly consider the first type.

If the traffic between s and x goes through only one route, then any relaying node on this route can easily observe the entire traffic between g and x, thus violating its traffic pattern privacy. To avoid this problem, x must establish multiple paths with g and distribute its traffic along these paths, such that any node can only get partial picture of x's traffic pattern.

However, the complete traffic pattern information of x could still be obtained by a single node in case of multi-path routing. In the example shown by Fig. 1.2, g allocates the traffic to x via three disjoint routes by fixed proportion. Then for any node along any path, although only seeing one third of the flow, the observed traffic shape is isomorphic to the original one. Therefore, the traffic to x must be distributed along multiple route in a time-variant fashion, such that the traffic pattern observed at any node is statistically deviant from the original pattern.

1.3.2 Traffic Entropy

We propose to use information entropy as the metric to quantify the performance of a solution at preserving the traffic pattern confidentiality. In what follows, we consider two nodes x and y. x is the destination node of the traffic from the gateway g to x. y is the observing node, which relays packets for x and also tries to analyze the traffic of x.

$\mathcal{V}$	wireless node set
$\mathcal{E}$	edge set
g	gateway node
x	destination node
y	observing node
X	random variable describing x's traffic pattern
Y^X	random variable describing x's traffic pattern observed by y
$H(X)$	entropy of X
$H(Y^X)$	entropy of Y^X
$I(Y^X, X)$	mutual information between X and Y^X

Table 1.1: Notations used in Sec. 1.3

Basic Definition

Ideally, we view the traffic of x as a continuous function of time, as shown in Fig. 1.3. In practice, the traffic analysis is conducted by dividing time into equal-sized sampling periods, then measuring the amount of traffic in each period, usually in terms of number of packets, assuming the packet sizes are all equal. Therefore, as the first step, we discretize the continuous traffic curve into piece-wise approximation of discrete values, each denoting the number of packets destined to x in a sampling period.

Now, we use X as the random variable of this discrete value. Y^X is the random variable representing the number of packets destined to x observed at node y in a sampling period. We denote $P(X = i)$ as the probability that the random variable X is equal to i ($i \in \mathcal{N}$), i.e., the probability that node x receives i packets in a sampling period. Likewise, $P(Y^X = j)$ is the probability that Y^X is equal to j ($j \in \mathcal{R}$), i.e., j packets destined to x go through node y in a sampling period.

Then the discrete Shannon entropy of the discrete random variable X is

$$H(X) = -\sum_i P(X = i) \log_2 P(X = i) \tag{1.1}$$

$H(X)$ is a measurement of the uncertainty about outcome of X. In other words, it measures the information of node x's traffic, *i.e.*, the number of bits required to code the values of X. $H(X)$ takes its maximum value when the value of X is uniformly distributed.

On the other hand, if the traffic pattern is CBR, then $H(X) = 0$ since the number of packets at any sampling period is fixed[4].

Similarly, we have the entropy for Y^X as follows.

$$H(Y^X) = -\sum_j P(Y^X = j) \log_2 P(Y^X = j) \tag{1.2}$$

Mutual Information

We then define the conditional entropy of random variable Y^X with respect to X as

$$H(X|Y^X) = -\sum_j P(Y^X = j) \sum_i p_{ij} \log_2 \ p_{ij} \tag{1.3}$$

where $p_{ij} = P(X = i|Y^X = j)$ is the probability that $X = i$ given condition that $Y^X = j$. $H(X|Y^X)$ can be thought of as the uncertainty remaining about X after Y^X is known. The joint entropy of X and Y^X can be shown as

$$H(X, Y^X) = H(Y^X) + H(X|Y^X) \tag{1.4}$$

Finally, we define the mutual information between X and Y^X as

$$\begin{aligned} I(Y^X, X) &= H(X) + H(Y^X) - H(X, Y^X) \\ &= H(X) - H(X|Y^X) \end{aligned} \tag{1.5}$$

which represents the information we gain about X from Y^X.

Back to the example in Fig. 1.2, let us assume that the observing node y is located on one route destined to x. Since the traffic shape observed at y is the same as x, at any sampling period, if $Y^X = j$, then X must equal to a fixed value i, making $P(X = i|Y^X = j) = 1$. According to Eq. (1.3), this makes the conditional entropy $H(X|Y^X) = 0$. According to Eq. (1.5), we have $I(Y^X, X) = H(X)$, implying that from Y^X, we gain the complete

[4]This offers the information-theoretic interpretation for traffic padding: by flattening the traffic curve with blank packets, the entropy of observable traffic is reduced to 0, which perfectly hides the information of the original traffic pattern.

information about X.

On the contrary, if Y^X is independent from X, then the conditional probability $P(X = i|Y^X = j) = P(X = i)$, which maximizes the conditional entropy $H(X|Y^X)$ to $H(X)$. According to Eq. (1.5), we have $I(Y^X, X) = 0$,[5] i.e., we gain no information about X from Y^X.

In reality, since Y^X records the number of a subset of packets destined to node x, it can not be totally independent from the random variable X. Therefore, the mutual information should be valued between the two extremes discussed above, *i.e.*, $0 < I(Y^X, X) < H(X)$. This means that node y can still obtain partial information of X's traffic pattern. However, a good routing solution should minimize such mutual information as much as possible for any potential observing node. More formally, we should minimize

$$\max_{Y \in \mathcal{V}-X} I(Y^X, X) \tag{1.6}$$

the maximum mutual information that any node can obtain about X.

1.4 Penalty-based Routing Algorithm

In this section, we propose a penalty-based routing algorithm to achieve our goal of hiding traffic pattern by exploiting the richness of available paths between two nodes in WMN. Specifically, we choose to adopt the *source routing* scheme. Such a choice is enabled by the fact that one node can easily acquire the topology of the WMN it belongs to, which is mid-sized (within 100 nodes) and static.

When designing the algorithm, we also keep in mind the need to compromise between sufficient security assurance and acceptable system overhead. We would show in our algorithm that system performance is satisfactory and security assurance is adequate.

Shown in Tab. 1.2, the algorithm operates in three phases, *path pool generation*, *candidate*

[5]By the definition of mutual information, $I(Y^X, X) \geq 0$, with equality if and only if X and Y are independent.

path selection and *individual packet routing*.

First, in the path pool generation phase, we try to generate a large set of diversified routing paths connecting the gateway g and the destination node x, denoted as S_{paths}. The path generation algorithm is an iterated process of applying a modified version of Dijkstra's algorithm. Here, each node is assigned a penalty weight, and the weight of an edge is defined as weighted average of penalty weights of its two end nodes. The weight (or cost) of a path is defined as the sum of penalty weights of all edges consisting this path. The algorithm runs in iterations. Initially, we set the penalty weight of each node as 1, then run the Dijkstra's algorithm to find the first shortest path from the gateway g to x. Next, we increase the penalty weight for each node on this found path. This will make these appeared nodes less competitive to other nodes in becoming components of next path. After this, the algorithm proceeds to the next iteration, generating the second path, and all nodes appearing on the second path are penalized through increasing their weights. This process goes on until enough number of paths are found.

Second, in the candidate path selection phase, we try to choose a combination of diversified routing paths, a subset of paths from the set S_{paths} , denoted as $S_{selected}$. The paths in $S_{selected}$ are selected randomly from S_{paths}. After each choice of a path into $S_{selected}$, the probability factor of that path is decreased to lower the chance of multiple identical paths existing in $S_{selected}$. $S_{selected}$ is changed and renewed corresponding to network activities.

Third, in the packet routing phase, we choose randomly from $S_{selected}$ one path for each packet and increase the counter for the selected path subset $S_{selected}$. This $S_{selected}$ path subset expires after counter reaches its predetermined threshold. Then $S_{selected}$ is renewed by calling the second phase again.

Since packets are assigned a randomly chosen path, and all these candidate paths are designed to be disjoint, the chance that packets are routed in similar paths is small. Our experiment results further confirm this intuition.

This algorithm is designed to balance the needs of routing performance (finding paths with smallest hop count) and preserving traffic pattern privacy (finding disjoint paths). The

penalty weight update function serves as the tuning knob to maneuver the algorithm between these two contradictory goals. During the initialization, when the penalties of all nodes are equal, the path found by the algorithm is indeed shortest in terms of hop count. As a node is chosen by more routes, its penalty weight monotonically increases, making it less likely to be chosen again. Thus, as the algorithm proceeds, the newly-chosen paths (shortest in terms of its aggregate penalty weight) become more disjoint from existing paths, but longer in terms of hop count. The pace of such shift from "smallest hop-count path" to "disjoint path" is controlled by how fast the penalty weight update function grows. Our experiment results confirm us this reasoning. Finally, by randomly assigning packets along different paths, the algorithm maximally disturbs the traffic pattern of any $g - x$ pair.

Although penalty-based routing has been used in existing literature [8], we are using it for different objects. Their links were penalized for losses or malicious behavior while our approach applies it avoid using links repeatedly to get better path diversity.

1.5 Experimental Results

1.5.1 Simulation Setup

We base our simulation on a randomly generated topology (Fig. 1.4) (600 x 600) with 30 nodes. The effective distance between two nodes is set to be 250. The whole process of simulation consists of 400,000 logical ticks. In each single tick, a packet is generated at gateway node 0 and its destination is randomly decided to be one of the other 29 nodes. To better simulate real network traffic, we set the probability of 0.05 that at one tick no packet is generated, i.e., idle probability. The distance delay factor is chosen to be 0.003 tick and hop delay factor is decided as 0.05 tick. We approximate hop delay at any node by multiplying hop delay factor with its usage count by all paths chosen initially.

With a relatively small node set, we choose 50 as our $PathPoolSize$ and 5 as $SelPathNum$. The selected path subset $S_{selected}$ for any destination node is renewed after sending 50 packets to that node. To obtain multiple diversified paths with Dijkstra's algorithm more quickly,

/*Penalty-Based Shortest Path*
$PBSP(Snode, Dnode)$
  For each node $v \in \mathcal{V}$
    $d[v] \leftarrow \infty$
  For each node $v \in \mathcal{V}$
    $prev[v] \leftarrow \infty$
  For each node $v \in \mathcal{V}$
    $visited[v] \leftarrow 0$
  $d[SNode] \leftarrow 0$
  Repeat
    Get unvisited vertex v with the least $d[v]$
    If $d[v] \geq \infty$, **Then** v unreachable
    Else $visited[v] \leftarrow 1$
    For all v's neighbors w
      $EdgePenalty = \alpha[pow(\gamma, (w.tag))] + \beta(v.tag)$
      If $d[w] > d[v] + EdgePenalty$
        $d[w] \leftarrow d[v] + EdgePenalty$
        $prev[w] \leftarrow v$
  Until $visited[v] = 1, \forall v \in \mathcal{V}$

/*Generate S_{paths} For Each $g - x$ Pair*/
$GenPath()$
For All Non-Gateway Nodes x
  For each node $v \in \mathcal{V}$
    $v.tag \leftarrow 1$
  Repeat
    PBSP(g, x)
    Get new $g - x$ path P_{new} from vector $prev[]$
    Store P_{new} in S_{paths}
    For all nodes v on P_{new}
      $v.tag \leftarrow v.tag + 1$
  Until $PathPoolSize$ paths found.

/*Select $S_{selected}$ For Each $g - x$ Pair*/
$SelPath()$
Repeat
  $rnd = rand()\ mod\ PathPoolSize$
  select rndth path from S_{paths}
Until $SelPathNum$ paths selected

/*Decide path for arriving packet*/
$RoutePkt(Snode, Dnode)$
  $Packets[Dnode] \leftarrow Packets[Dnode] + 1$
  $rndpath = rand()\ mod\ SelPathNum$
  route packet along the $rndpath$th path from $S_{selected}$
  If $Packets[Dnode] > ReSelPathCnt$
    $Packets[Dnode] \leftarrow 0$
    SelPath()

Table 1.2: Penalty-based Routing Algorithm

v, w	node
$v.tag$	number of times v is included by a path
α	factor to slow down penalty rate
β	factor to avoid many identical paths in beginning stages of path generation
γ	base of exponential penalty function
$d[]$	penalty vector for every node
$prev[]$	vector to store P_{new} reversely
$Packets[]$	vector to store number of arrived packets for every node

Table 1.3: Notations used in Sec. 1.4

we introduce exponential penalty function on tag of one node and used γ as the base of exponential function when deciding on which edge to include to candidate path. To slow down growing rate of exponential penalty function, we multiply the exponential function with a factor α when calculating $EdgePenalty$. To avoid getting too many identically paths in beginning stages, we amplify influence of another node by multiplying tag of another node with β. The penalty parameters α, β, γ are chosen to be 0.5, 15 and 1.85, respectively.

1.5.2 Traffic Entropy and Mutual Information

The total 400,000 ticks is divided into 20 periods. Each period is then divided into 50 intervals and one interval is 400 ticks long. Within each interval, for each destination node x, we count the number of packets that all other nodes y has relayed for x. Then for each period, we independently calculate the traffic entropies $H(X)$, $H(Y^X)$, and mutual information $I(Y^X, X)$ based on their definitions in Sec. 1.3.2.

Due to the space limit, we only show part of our results. Among all nodes in the network, we choose two sets of nodes. Nodes in the first set $\{1, 6, 11, 15, 23, 24, 25, 29\}$ are close to (2 to 3 hops) the gateway node 0. Nodes in the second set $\{2, 3, 7, 16, 17, 28\}$ are at the edge of the network, 4 to 5 hops away from the gateway. We choose two representative nodes, 1 and 16, out of each set.

Fig. 1.5 shows the variance of traffic entropy and mutual information along the time. In Fig. 1.5 (a), $H(1-1)$ denotes the traffic entropy of node 1. $H(23-1)$ denotes the traffic entropy of node 23 based on its observation on node 1. $MI(23-1, 1-1)$ denotes the mutual

information node 23 shares with node 1. The same notation rules apply for Fig. 1.5 (b), where node 16 is the destination, and 9 is the observer. In both pictures, the observing node only shares 40% or less of information about the observed destination node at any sampling period.

This observation is further confirmed in Fig. 1.6, where we plot the time-variant mutual information that destinations 1 and 16 share with other randomly-chosen observing nodes. These results show that with our algorithm, the destination node is able to consistently limit the proportion of mutual information it shares with the observing nodes.

1.5.3 Which Nodes have more Mutual Information?

In Fig. 1.7 (a), we calculate the time-averaged mutual information for all observing nodes with respect to the destination node 1, and sort them in the ascending order. Here, we observe an almost linearly-growing curve except at its head and tail. For nodes at the head of the cure, their mutual information is 0 since they lie at the outer rim of the network, hence are not chosen by our routing algorithm to relay traffic for node 1. At the tail of the curve is destination node 1, whose mutual information is actually the traffic entropy of its own. In Fig. 1.7 (b), we observe the same phenomenon for destination 16, except at the head of the curve. This is because its network location is at the opposite end of the gateway, making every node of the network to be its candidate relaying node.

This leads us to investigate if such distribution of mutual information is related with any other factors. We tried to connect mutual information of each node with certain metric, such as its distance to the destination, but failed to find any causal relationship. We then sort observing nodes based on the averaged relayed traffic (average number of packets each node relays in a sampling period) on a log-log scale, and find the linear distribution as shown in Fig. 1.8.

Obviously, such a power-law correlation tells us that more traffic an observing node relays for a destination node, the more mutual information can be obtained about its traffic entropy. Furthermore, it gives us one way to experimentally quantify the relationship of these two

metrics. Let T be the amount of traffic relayed and I be the mutual information, then their power-law relationship can be written as

$$I = aT^k \tag{1.7}$$

where a is the constant of proportionality and k is the exponent of the power law, both of which can be measured from Fig. 1.8. If $k < 1$, then the mutual information of an observing node grows in a sub-linear fashion as the amount of its relayed traffic increases, and in a super-linear fashion otherwise. From what we have in Fig. 1.8 and the same results for other destination nodes, $k < 1$. This means that each time to make its mutual information further grows with the same increment, an observing node has to relay more and more traffic.

1.5.4 Trade-off between Performance Degradation and Traffic Privacy

Finally, we study the performance trade-off of our algorithm by tuning its exponential penalty function base γ. The performance degradation introduced by our algorithm is captured by the average hop ratio. For each gateway-destination pair $g - x$, this metric is defined as the ratio between the average number of hops a packet goes through using our algorithm and the number of hops of the shortest path between g and s. From Fig. 1.9, we can see that the average hop ratio increases as γ increases. The direct neighbors of the gateway are less sensitive to the change of γ, like node 6 in Fig. 1.9(a) and node 23 in Fig. 1.9(b).

In Fig. 1.10 and Fig. 1.11 we find that under shortest path routing, the mutual information of a node is 0 if it is not on the path to destination node. Otherwise, the mutual information node is much higher than the case of our algorithm. Also worth noting is that increasing of γ has different impact on different node, depending on its distance to gateway, destination, and its location in the WMN. Take node 12 (Fig. 1.10) and 6 (Fig. 1.11) for example, since they lie near to gateway node and are relatively centrally situated, their observed mutual information vary little with respect to the change of γ. Whereas for node 22 (Fig. 1.10), which is far away from destination node 1 and on edge of WMN, mutual information shared between itself and node 1 increases with the growth of γ, indicating more traffic is routed through

farther nodes. This tendency of routing packets from farther nodes leads to higher average number of hops, which is confirmed by our analysis about average hop ratio. However, traffic mutual information tends to decrease once the γ parameter gets too high (2.59 in this figure). This is due to the fact that when penalty values of many possible edges get large quickly, their relative differences become less. Consequently candidate paths become less. The great fluctuation of node 26 (Fig. 1.10) is due to its position in center of topology and equal distance to both gateway and destination. Similar observations can be made about mutual information values of destination node 16 (Fig. 1.11).

We also observe from Fig. 1.12 that our algorithm achieves our goal of preserving traffic pattern. In the first place, it is easy to conclude that in normal shortest path routing, all relaying nodes shares the same traffic information with destination node, as shown by the tail of the ShortestPath curve in Fig. 1.12. However, for our algorithm, the mutual information shared between relaying nodes and destination node varies much less among all relaying nodes. And the higher γ is, the more leveled off the curve becomes, and the closer we are to the goal of minimizing the greatest mutual information, formulated in Eq. 1.6. It is also interesting to observe that mutual information is 0 for some nodes far away from both gateway and destination. For example, in Fig. 1.12 (a), when destination is 1, while all nodes participate in relaying packets for destination 16, since destination and gateway nodes are in opposite directions with respect to WMN topology.

1.6 Collusion Analysis

The relative small size of a typical WMN makes it easy for spatially close eavesdroppers to find each other. This alarms us the high possibility of collusion of two malicious observers by exchanging their observed traffic pattern. This motivates us to make our proposed solution resilient to such collusion threats.

To analyze the extent to which collusion reveals about original traffic pattern, we study the fluctuation of the observed traffic information. In this way, we can know how much in addition the colluders can observe about the original traffic.

1.6.1 Problem Description

In the former part of this chapter we focused on traffic confidentiality, and studied the problem of traffic pattern concealment via routing control. However, the relative small size of a WMN, aided by the stationary adjacent routers, invites a high possibility of collusion of several observing relaying routers in the community. Since it is highly possible that different observers will know about various "ups and downs" of target's traffic, if malicious observers interchange their observed traffic information of target users, the combined observation could reveal significant portion of original traffic pattern. This is illustrated in Fig. 1.13.

Given the size of community network (less than 100 neighbor nodes), we have a reasonable estimation that three or more malicious observers are unlikely to exist simultaneously, and hence we will focus on analysing the collusion problem of two observers in this work.

The parameters that affect significantly our collusion analysis include the choice of co-operating observers and destination target node. Since any routing algorithm will largely depend on topology of the network, the relative positions of observers, source and destination nodes can affect portions of revealed traffic pattern greatly. Another important parameter is the base of exponential penalty function explained in Sec. 1.4.

1.6.2 Colluded Traffic Mutual Information

Our modelling of colluded traffic analysis tries to study the influence of collusion to observed traffic patterns of every period. This can help us to evaluate the resilience of our proposed PBSP routing algorithm against collusion attack. In what follows, we consider three nodes x and y, z. x is the destination node of the traffic from the gateway g to x. Nodes y, z are the observing nodes, which relay packets for x, and also try to analyze the traffic of x. Due to the uncertainty of routing, y, z may or may not be on the same path over time.

To begin with, we need to identify a measurement for colluded observations. Based on definition of traffic mutual information defined in Sec. 1.3.2, we can measure the colluded observation about destination x with mutual information between x and (y, z). The traffic

$\mathcal{V}$	wireless node set
$\mathcal{E}$	edge set
g	gateway node
x	destination node
y, z	observing nodes
X	random variable describing x's traffic pattern
Y^X, Z^X	random variables describing x's traffic pattern observed by y, z, separately
(Y^X, Z^X)	random variable describing x's traffic pattern observed by y, z together
$H(X)$	entropy of X
$H(Y^X)$	entropy of Y^X
$H(Y^X, Z^X, X)$	joint entropy of Y^X, Z^X, X
$I(Y^X; X)$	mutual information between X and Y^X
$I(Y^X, Z^X; X)$	colluded mutual information between X and (Y^X, Z^X)

Table 1.4: Notations used in Sec. 1.6.2

observations by y and z together can be deemed as joint distribution of variable Y^X and Z^X. The colluded traffic mutual information $I(Y^X, Z^X; X)$ of random variable (Y^X, Z^X) with respect to X can then be defined as

$$I(Y^X, Z^X; X) = H(Y^X, Z^X) + H(X) - H(Y^X, Z^X, X) \tag{1.8}$$

where $H(Y^X, Z^X, X)$ is the joint entropy of Y^X, Z^X and X. $I(Y^X, Z^X; X)$ can represent the information we could gain about X from (Y^X, Z^X), i.e., from y, z together. Their relationship is shown in Fig. 1.14

1.6.3 Simulation Results

For ease of notation, in following discussion, we would use $H(Y, X)$ to denote $H(Y^X, X)$, i.e., the entropy of traffic that y observes about x. Similarly, we simplify the joint traffic entropy $H(Y^X, Z^X)$ as $H(y, z, x)$, where Y^X, Z^X denote the portions of traffic that Y, Z observes about X. In a subtly different way, we denote $I(Y^X; X)$ as $I(Y; X)$ and $I(Y^X, Z^X; X)$ as $I(Y, Z; X)$.

Traffic Curves

In the first place, we will present the measured traffic curves along time line. In Fig. 1.15, node 1 is destination and we can easily conclude that its traffic (node 1 observing itself) is always the largest in amount. This is because any node can observe the whole traffic of itself while other nodes can only observe a portion of it.

Another observation we can make is the fact that the colluded knowledge about traffic activity of node 1 (in squares), as expected, is higher than any single observer, either 15 or 28. Moreover, we are confirmed by this traffic curve figure that, although generally speaking, node 15 observes much more traffic of node 1, during some intervals, node 28 out-performs 15 and elevates the aggregated knowledge about traffic activity of node 1. Example intervals are those near interval 100 and 150.

Colluded Traffic Mutual Information: Single Pair of Observers

Our next results are the comparisons of colluded traffic mutual information ($I(y,z;x)$), single observer mutual information ($I(y;x)$ and $I(z;x)$), original traffic entropy ($H(x)$), separately observed traffic entropy ($H(y,x)$ and $H(z,x)$) and joint entropy ($H(y,z,x)$).[6] From our analysis in Sec. 1.6.2, we can conclude the following relations among these values:

1. $H(y,x), H(z,x) \leq H(y,z,x) \leq H(x)$;
2. $I(y,x), I(z,x) \leq I(y,z,x) \leq H(x)$;
3. $I(y,x) \leq H(y,x) \leq H(x)$;
4. $I(z,x) \leq H(z,x) \leq H(x)$;

Now we can verify if the simulation results shown in Fig. 1.16 satisfy these relations. This means our modeling of traffic activity not only characterizes the traffic pattern fluctuation along the time, but also stands with the test of collusion problem. The simulation results of our model conforms with our conjecture.

[6]Please note that $H(y,z,x)$, according to our notation, means $H(Y^X, Z^X)$.

The overlapping curves in Fig. 1.16(b) indicates node 23 does not observe any traffic of node 1. This could be true since 23 and 1 are on the opposite side of the network.

On the other hand, Fig. 1.17 shows similar results, except for this time node 16 is the destination.

Colluded Traffic Mutual Information: Multiple Pairs of Observers

Now that the simulation results have satisfied the necessary relations listed in previous part, we would like to know how collusion can affect the performance of Penalty-based Shortest Path (PBSP) routing algorithm under discussion. To do so, we will study the colluded traffic mutual information of several pairs of observers in one figure. In this way, we can compare the ratio of traffic information revealing of different pairs of observers.

From Fig. 1.18 we can observe that the conditions above still hold. Additionally, based on average values of the colluded traffic mutual information curves in both figures, we can guess that the PBSP algorithm still works well when there are two observers colluding to share their knowledge about one destination.

To further confirm this conjecture, we can examine another set of simulation results, as shown in Fig. 1.19. The colluded traffic mutual information of all observer pairs in this figure does not exceed half of total traffic information either. In Fig. 1.19(b), however, we notice some small error of curves, i.e., the value of $I(15, 6; 16)$ is a little less than that of $I(15; 16)$ for period 2. Although this is a small error, it reminds me of an approximation when computing $H(Y^X, Z^X, X)$. Instead of employing three parallel *PacketCounter* to get the aggregate traffic information, the simulation program approximates it based on the packet count value dictionary, which results in a lower $I(Y^X, Z^X; X)$ value.

The same explanation applies for the discrepancy in Fig. 1.20(a). In the mean time, the average value of colluded traffic mutual information of all observer pairs in Fig. 1.20 remains approximately less than half of the traffic entropy of target node along the time.

1.7 Related Work

Nowadays multi-hop wireless mesh network (WMN) is gaining more popularity. Current deployments of WMN either serve as a substitute of traditional WLAN internet connection, or aim at providing infrastructural large-scale network access. [24]

Existing research [3, 19, 10, 7] on WMN has focused on how to better utilize the wireless channel resource and enhance its performance. For example, some researchers try to derive the optimal node density following capacity analysis in [18], while others strive to devise more efficient [13] protocols. A survey paper [6] by Akyildiz et al. provides a good source for existing and ongoing researches about wireless mesh networks. Some of the proposed solutions include equipping mesh routers with multiple radios and distributing the wireless backbone traffic over different wireless channels, routing the traffic through different paths [15, 33], or a joint solution of these two [26, 25]. Theoretical study shows that these approaches can significantly increase the capacity of WMN [22, 21]. These results make a significant step towards enabling WMN as an attractive alternative for broadband Internet access.

Information Theory is widely used and proves to be a useful tool. It works in situations where variations are frequent and unpredictable and helps to identify pattern and extent of variation. Serjantov et al. [29] define an information theoretic anonymity metric and suggest developing more sophisticated probabilistic anonymity metrics. Existing research [20], in the Internet setting , employs information theoretical coding, which is too complex and impractical for WMNs. The book [23] by David Mackay provides a good source for background knowledge in information theory.

Privacy has been a major concern of Internet users [12, 31]. In the existing literature of traffic pattern concealment, anonymous overlay routing [34, 9, 16, 20, 17, 14, 28] and traffic padding [30] have been proposed to preserve user traffic privacy and increase the difficulty for traffic analysis [27, 9]. The former approach provides user anonymity in an end-to-end connection through layered encryption and multi-hop overlay routing. The latter one conceals the traffic shape by generating a continuous random data stream at the link level.

However neither of them can be applied to WMN directly. First, the number of nodes in a WMN is limited. Second, traffic forwarding relationship among nodes is strongly dependent on their locations and the network topology. To better utilize the wireless channel resource and enhance the data delivery performance, a short path is usually selected; or a load-balanced routing scheme is employed. Such observations show that the anonymity systems, which rely on relaying traffic among nodes (randomly selected out of thousands) to gain anonymity, can not effectively preserve users' privacy in WMN, or at the cost of significant performance degradation. On the other hand, traffic padding mechanism consumes a considerable amount of network bandwidth, which makes it impractical in resource-constrained WMNs.

The schemes designed in wireless ad-hoc networks [32, 11] are more focused on location and identity privacy. While these are still issues in WMN, the traffic rates and temporal variations are more meaningful and consequential.

To the best of our knowledge, no existing works have studied collusion problems about traffic privacy in the scenario of Wireless Mesh Networks.

1.8 Conclusion

This chapter identifies the problem of traffic privacy preservation in wireless mesh networks (WMN). To address this problem, we start by introducing a light-weight architecture for WMN, then propose "traffic entropy", an information theoretic metric to quantify how well a solution performs at preserving the traffic pattern confidentiality, all of which pave the way to our penalty-based shortest path routing algorithm. Furthermore, we evaluate our scheme against collusion of two malicious nodes. Simulation results show that our algorithm is able to maximally preserve the traffic privacy, meanwhile managing the network performance degradation within the acceptable region. Our simulation analysis also proves the resilience of our solution against two colluding observers.

For the future work, we will focus on the following problems. First, although our algo-

rithm is evaluated in a single-radio, single-channel WMN setting, it can be easily enhanced to exploit the advantage of multiple radios and multiple channels available in WMNs. Performance evaluation of the enhanced algorithm in such settings will be interesting. It is also beneficial to research into the possibility of devising a distributed routing that achieves the same goal but supports better scalability.

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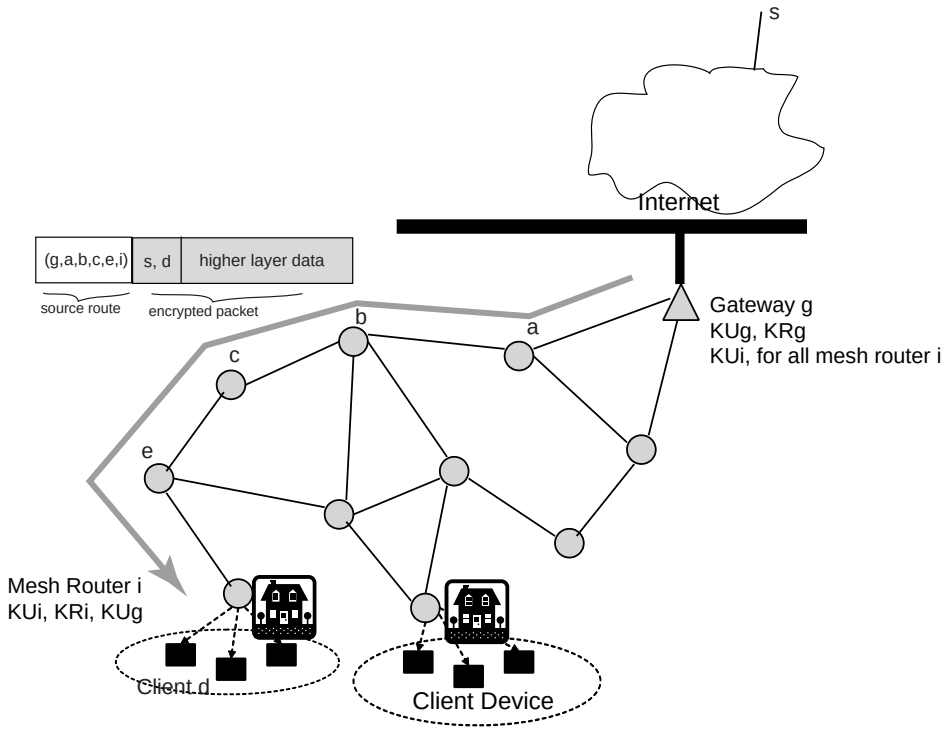


Figure 1.1: Privacy preserving architecture for wireless mesh network.

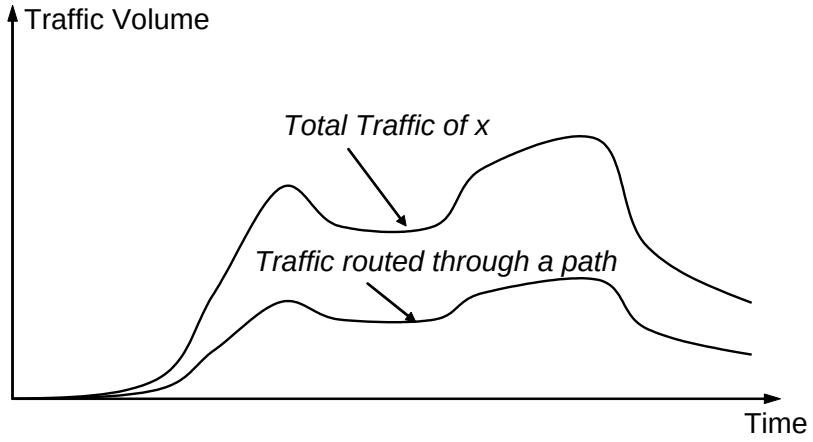


Figure 1.2: An Example of Isomorphic Traffic

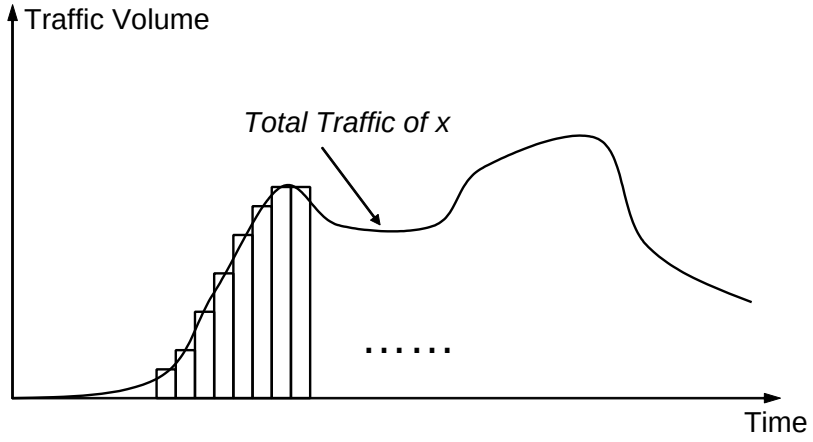


Figure 1.3: Sampling-based Traffic Analysis

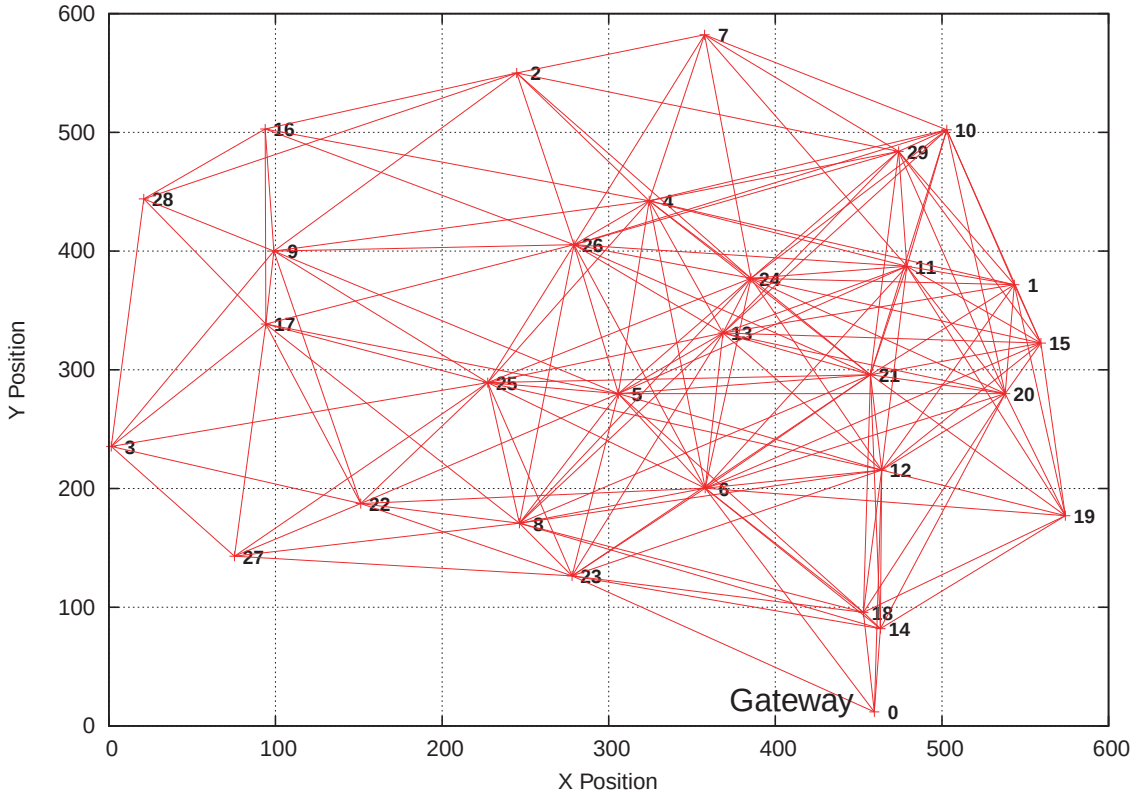
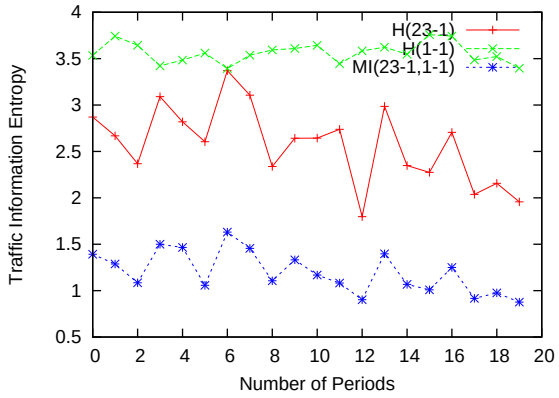
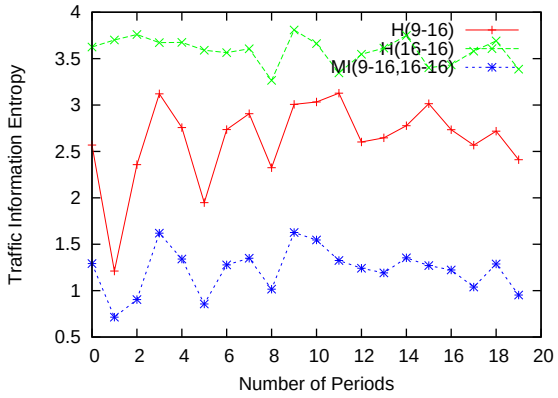


Figure 1.4: Experimental Topology

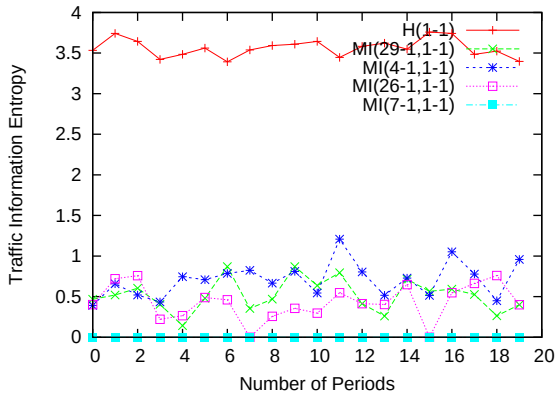


(a) Destination: Node 1, Observer: Node 23

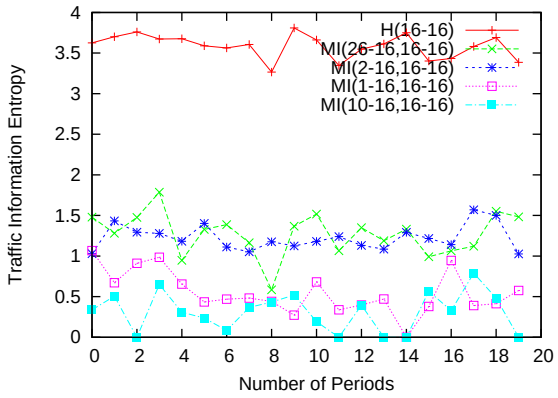


(b) Destination: Node 16, Observer: Node 9

Figure 1.5: Traffic Entropy along Time (Single Observer, $\gamma = 1.85$)

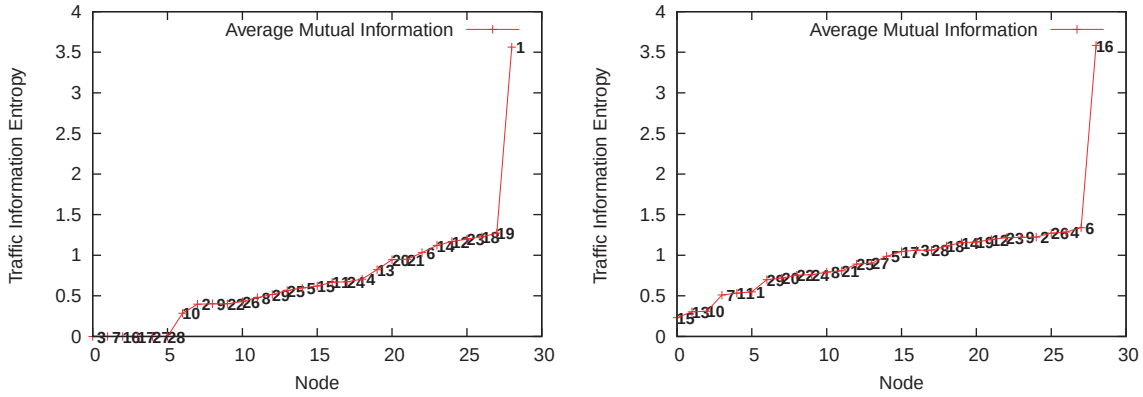


(a) Destination: Node 1, Observers: Node 4, 7, 26, 29



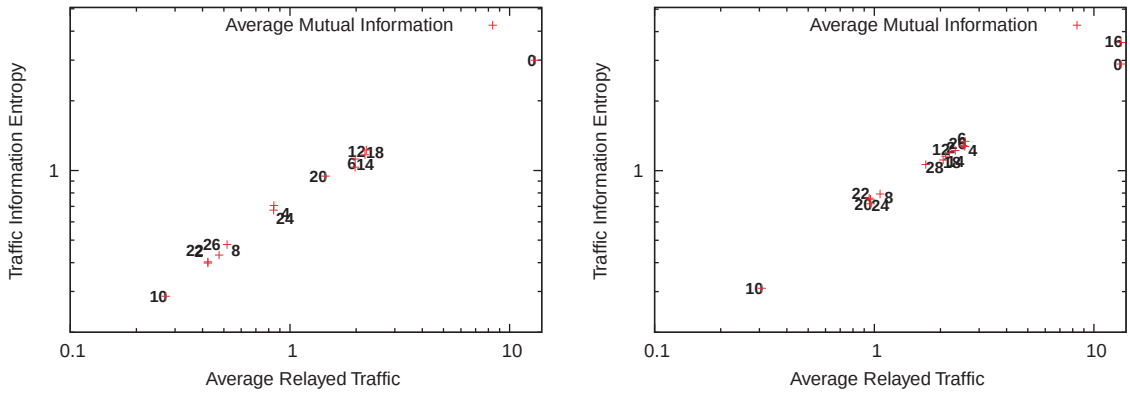
(b) Destination: Node 16, Observers: Node 1, 2, 10, 26

Figure 1.6: Traffic Entropy in Different Sampling Periods (Multiple Observers, $\gamma = 1.85$)



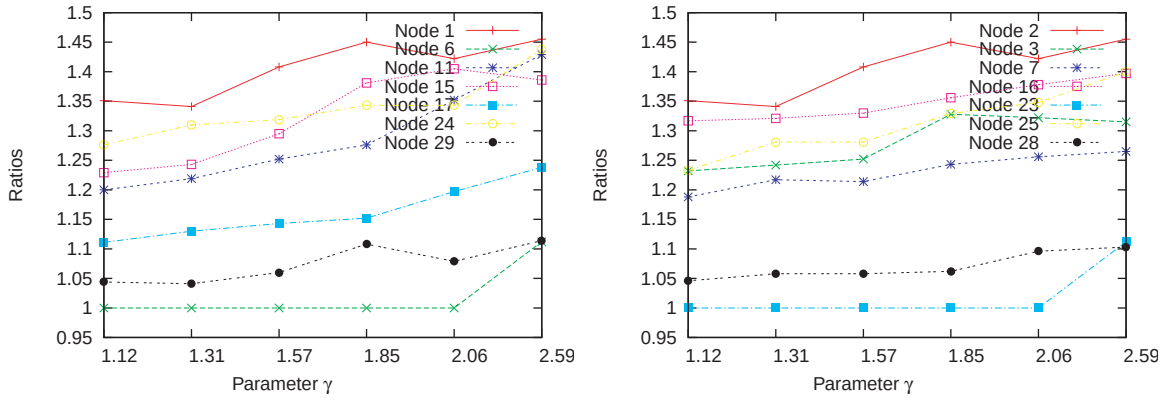
(a) Destination: Node 1 ($\gamma = 1.85$) (b) Destination: Node 16 ($\gamma = 1.85$)

Figure 1.7: Sorted Traffic Mutual Information



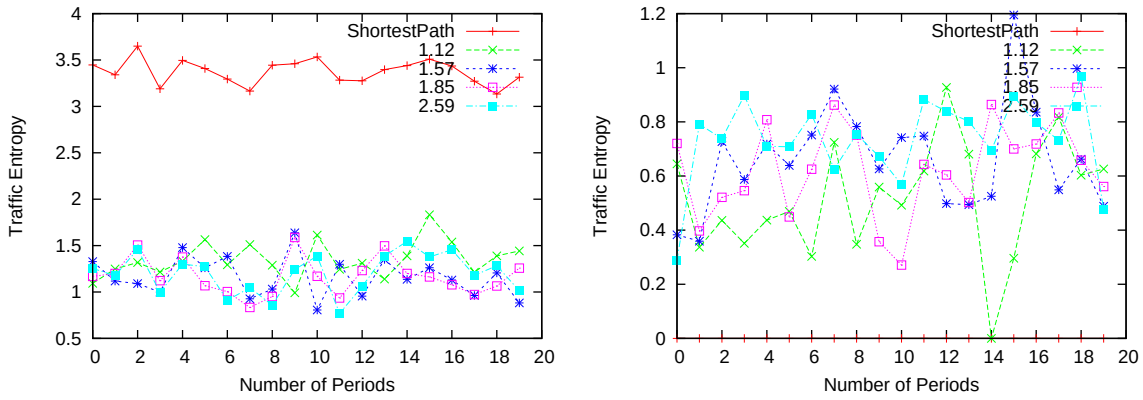
(a) Destination: Node 1 ($\gamma = 1.85$) (b) Destination: Node 16 ($\gamma = 1.85$)

Figure 1.8: Power-law Correlation of Mutual Information and Amount of Traffic Relayed



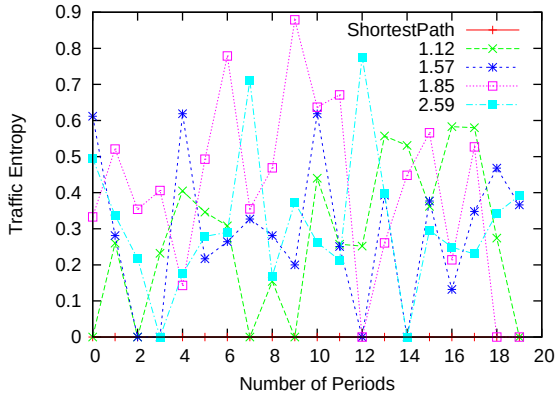
(a) Hop Ratio of Nodes in the First Set (b) Hop Ratio of Nodes in the Second set

Figure 1.9: Average Hop Ratio

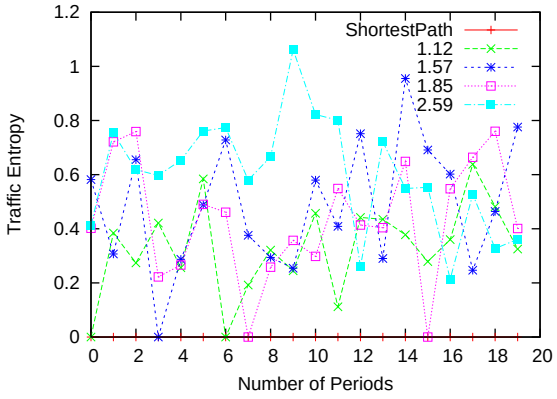


(a)Observer: Node 12

(b) Observer: Node 15

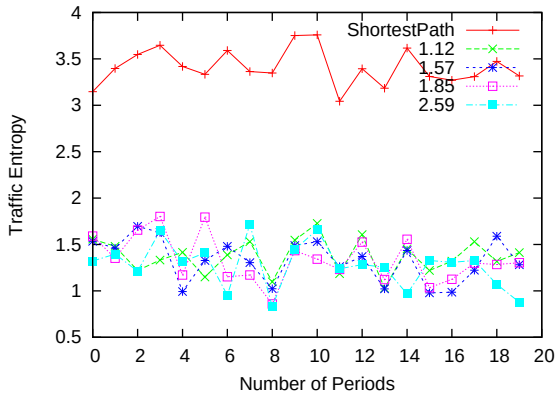


(c)Observer: Node 22

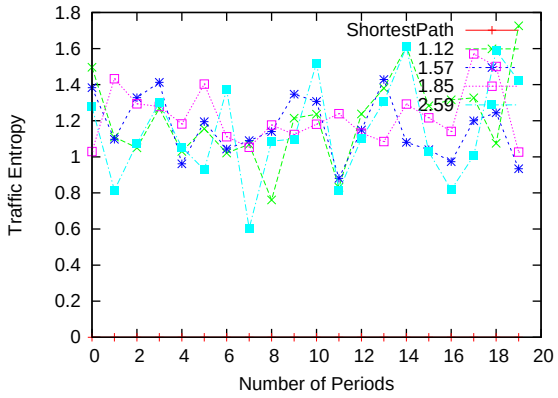


(d) Observer: Node 26

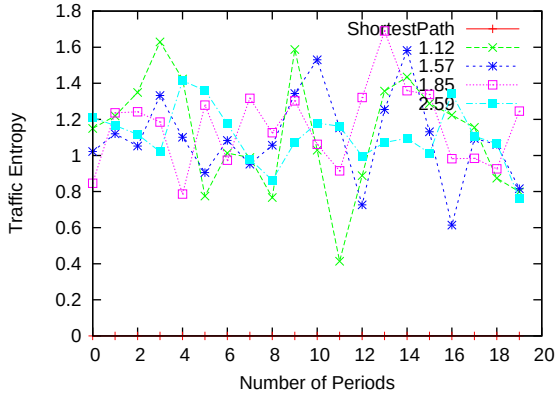
Figure 1.10: Traffic Mutual Information under Different Penalty Parameters (Destination: Node 1)



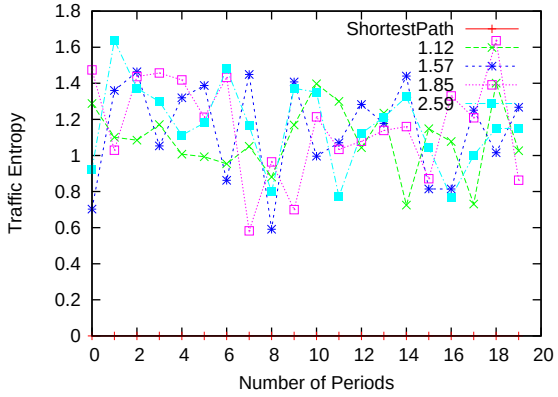
(a)Observer: Node 6



(b) Observer: Node 2

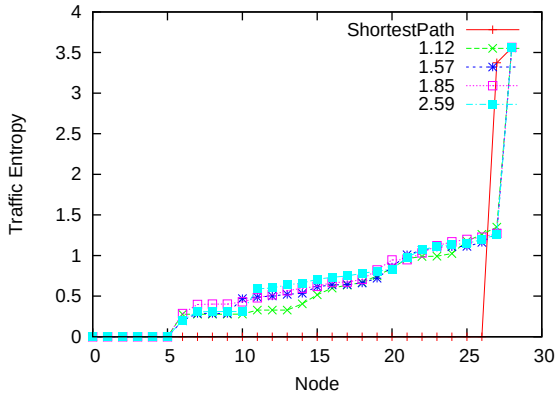


(c)Observer: Node 14

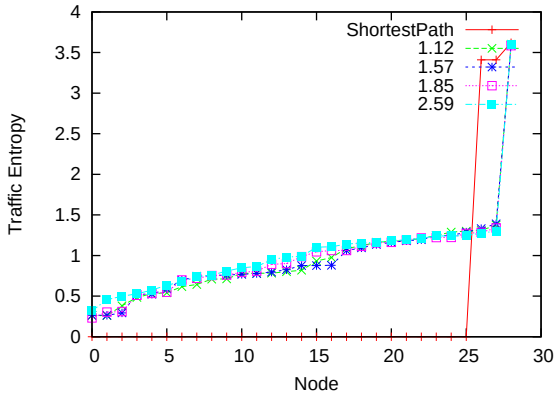


(d) Observer: Node 19

Figure 1.11: Traffic Mutual Information under Different Penalty Parameters (Destination: Node 16)



(a) Destination: Node 1



(b) Destination: Node 16

Figure 1.12: Sorted Traffic Mutual Information under Different Penalty Parameters

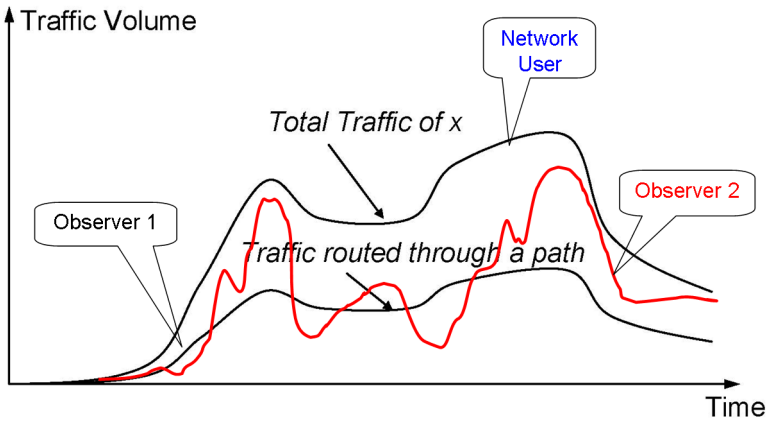


Figure 1.13: Collusion reveals significant portion of original traffic pattern

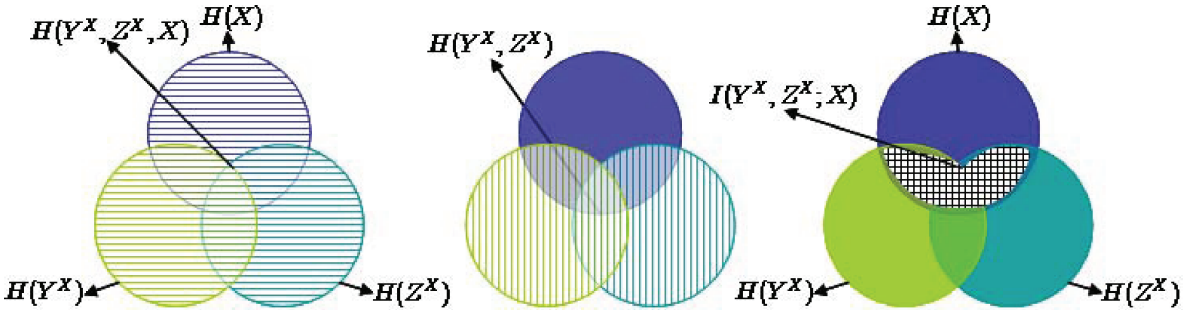


Figure 1.14: Vein graph representation of $I(Y^X, Z^X; X)$, $H(Y^X, Z^X)$ and $H(Y^X, Z^X, X)$.

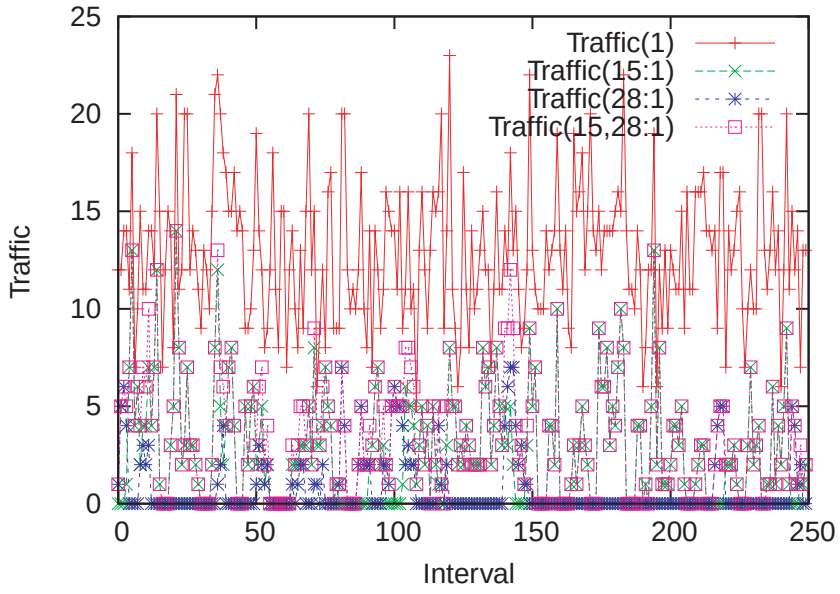
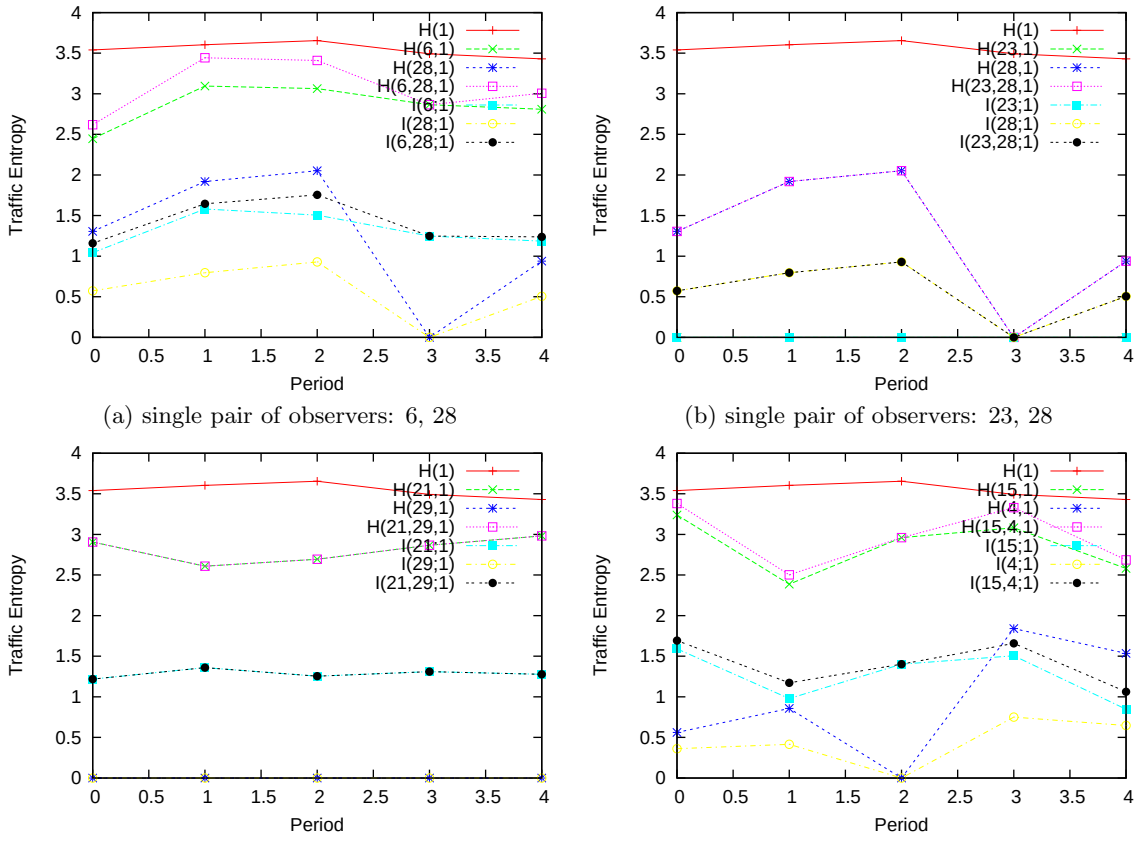


Figure 1.15: Sampled traffic curves from experiment.



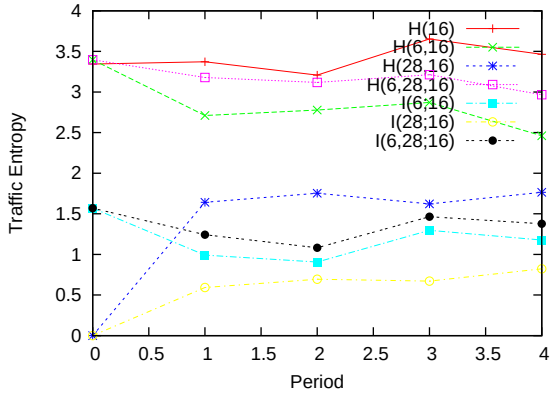
(a) single pair of observers: 6, 28

(b) single pair of observers: 23, 28

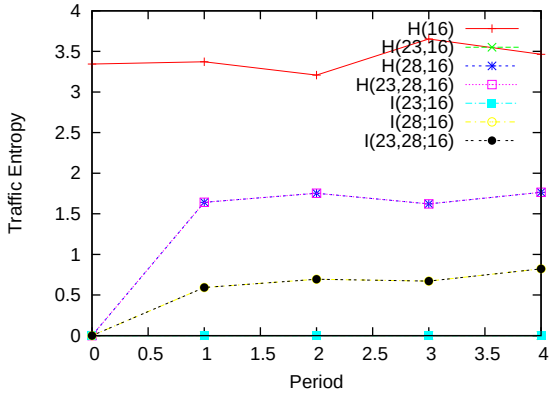
(c) single pair of observers: 21, 29

(d) single pair of observers: 15, 4

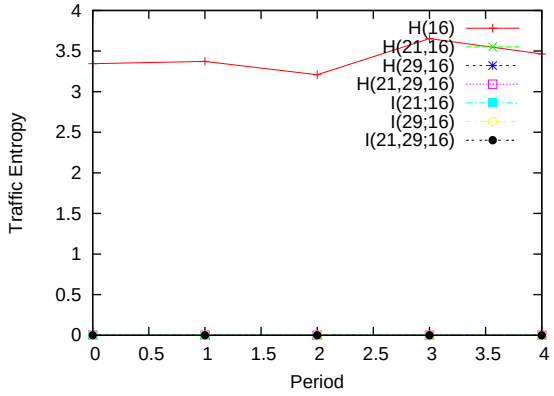
Figure 1.16: Colluded Traffic Mutual Information (destination: 1, $\gamma = 1.85$)



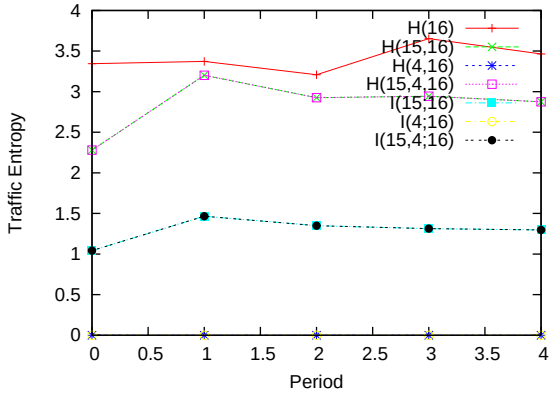
(a) single pair of observers: 6, 28



(b) single pair of observers: 23, 28

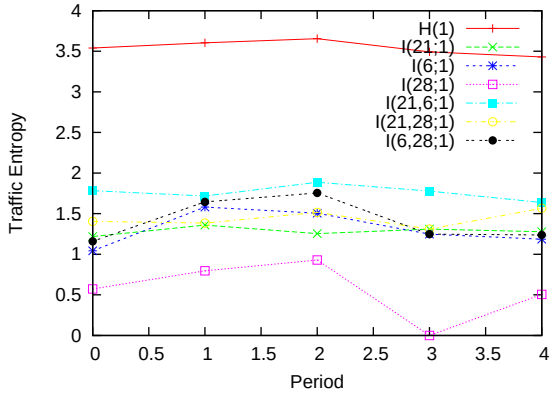


(c) single pair of observers: 21, 29

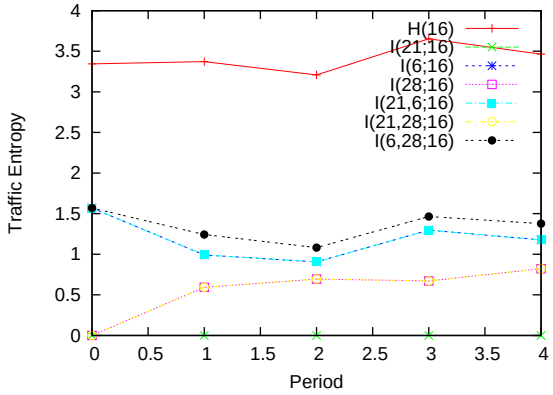


(d) single pair of observers: 15, 4

Figure 1.17: Colluded traffic mutual information (destination: 16, $\gamma = 1.85$)

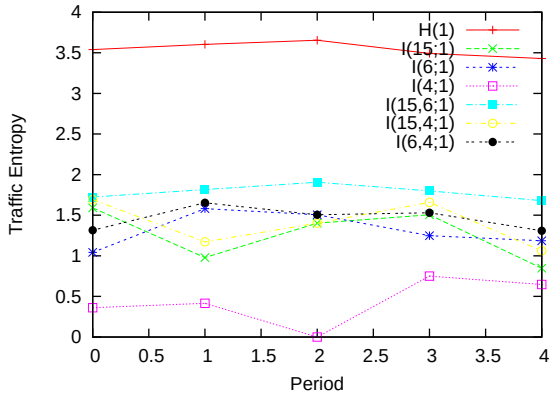


(a) destination: 1, observers: 21, 6, 28

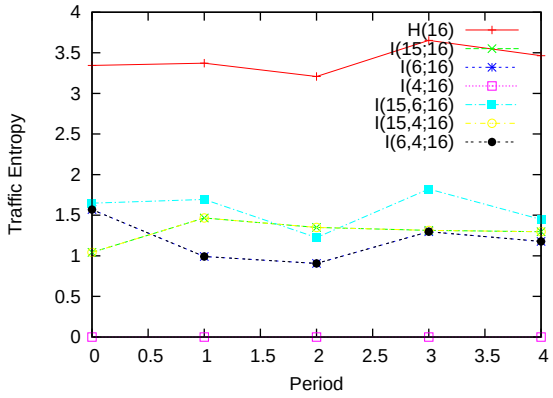


(b) destination: 16, observers: 21, 6, 28

Figure 1.18: Colluded traffic mutual information (multiple pairs of observers, $\gamma = 1.85$)

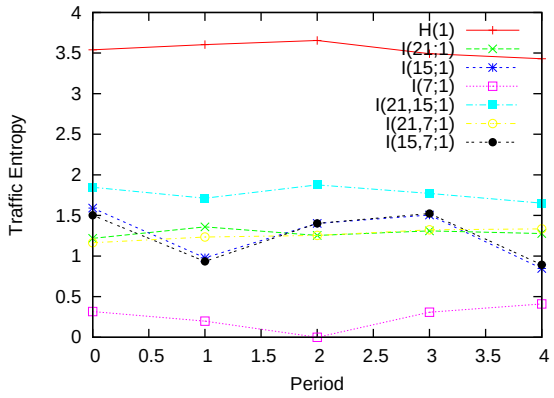


(a) destination: 1, observers: 15, 6, 4

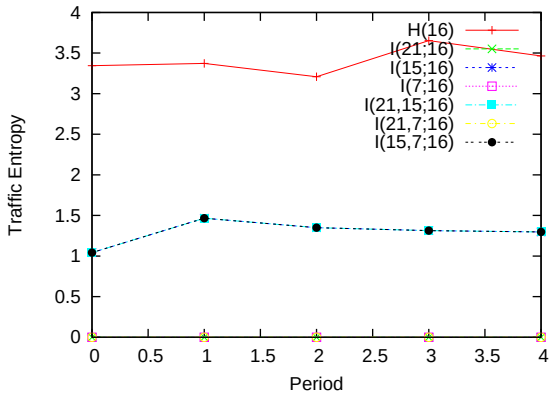


(b) destination: 16, observers: 15, 6, 4

Figure 1.19: Colluded traffic mutual information (multiple pairs of observers, $\gamma = 1.85$)



(a) destination: 1, observers: 21, 15, 7



(b) destination: 16, observers: 21, 15, 7

Figure 1.20: Colluded traffic mutual information (multiple pairs of observers, $\gamma = 1.85$)