# Air Force Institute of Technology
# Department of Electrical and Computer Engineering

CSCE 654 - Computer Communication Networks
Project #4 - Network Routing

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**Abstract**

The provided network design produced an average end-to-end delay of 101.19 ms. We incurred a total cost of $904.72M$ over 10 years. These parameters yielded a score of 160.876. If a buffer is needed, we would recommend implementing a buffer of $1MB$ on the 654SS server.

## Contents

# 1 Introduction:

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## 1.1 Optimization Process:

We optimized our network using the following methodology. Due to full-duplex communications, both directions of each link see the full link capacity. Thus, for any pair of bases $A$ and $B$, we only need to optimize for the highest load of $\lambda_{A\to B}$ or $\lambda_{B\to A}$.
We thus minimized the score function by changing the configuration of links between each pair of bases, giving an optimal 4-connected topology.
After we had our optimal configuration, we removed the two lowest-loaded links to achieve 3-connectedness. This prevented as much additional strain on the existing infrastructure as possible. We then optimized the remaining 8 links by routing the deleted channel's traffic through remaining channels. The 3-connected topology had a better score by $\approx 0.3$. This difference is small enough that the only way to know which network performs better is through simulation; thus, we are utilizing the 4-connected topology.

## 1.2 Network Topology:

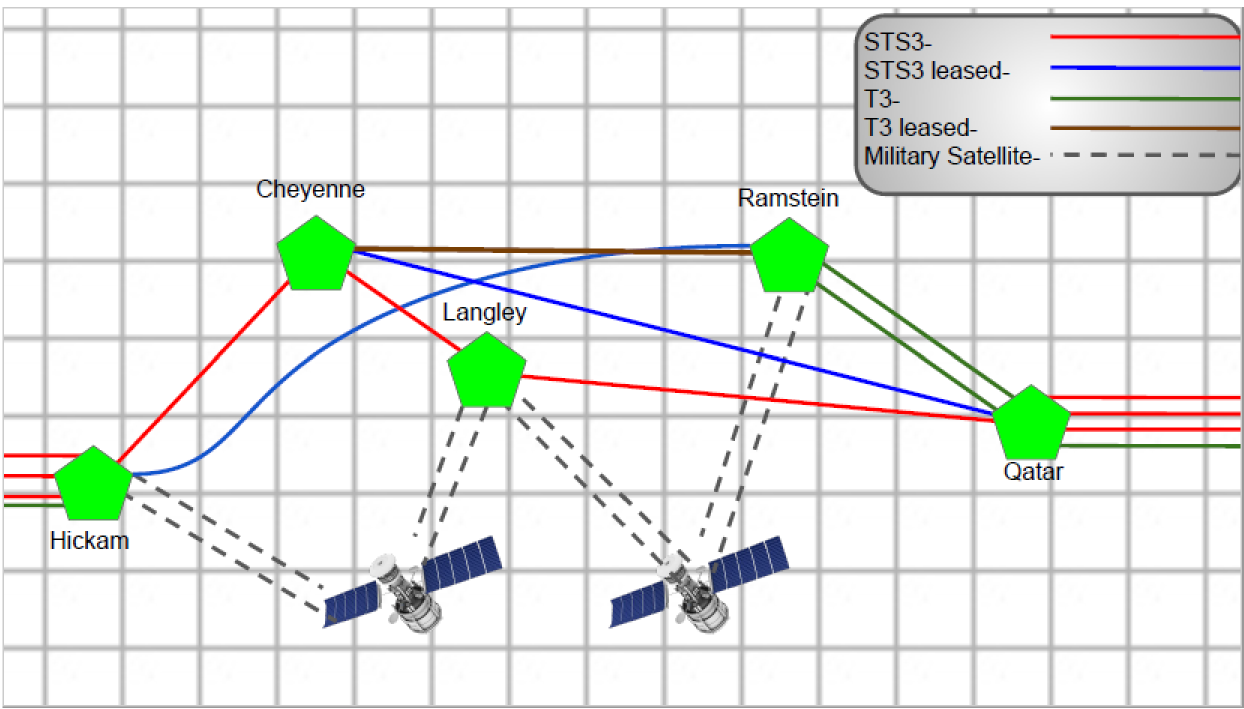


Figure 1: Network Topology of Routing Network

## 1.3 Traffic Load:

Table 1.3 shows the expected traffic load in packets per second, from each of the bases.

| Source | Load (pps) | Percent: |
|---|---|---|
| Hickam | 3950 | 40.72% |
| Cheyenne | 1050 | 10.82% |
| Qatar | 1500 | 15.46% |
| Langley | 1500 | 15.46% |
| Ramstein | 1700 | 17.53% |
| **Total:** | **9700** | **100.00%** |

Table 1: Traffic Load by Source

# 2 Methodology:

# 3 Cost:

Given the costs in the Project Requirements, we went through the following steps to build our total network cost.

## 3.1 Installation Costs:

For any leased system, satellite or otherwise, there was no installation cost. If there was an owned land line (STS-3 or T3), we incurred a trenching cost. This cost is calculated as follows, where $d$ is the distance between the two nodes:

$$\text{Trenching Cost } = IC_{trench} = d_{A\to B} \cdot \$10,000 \tag{1}$$

For owned land lines, we incurred a per-link installation cost.

$$\text{Link Installation Cost } = IC_{link} = d_{A\to B} \cdot \frac{cost}{km} \tag{2}$$

For any owned satellites (we have none), we would incur the following satellite installation cost, where $k$ is the cost of installing a given type of satellite:

$$\text{Satellite Installation Cost } = IC_{sat} = k \tag{3}$$

The overall installation cost is shown below:

$$\text{Installation Cost } = IC_{total} = IC_{trench} + IC_{sat} + \sum_{links} IC_{link} \tag{4}$$

## 3.2 Monthly Costs:

Each type of link had a given monthly cost, based on the type of link. Additionally, each node communicating with a satellite has a ground station. Our monthly cost ($MC$) was the sum of each link's monthly cost, plus the monthly cost of the 3 ground stations needed for satellite communication.[1]

## 3.3 Server Costs:

Each outbound link requires a server, so our total server cost is shown below, where $n$ is the total number of links

$$\text{Server Costs } = SC = 2 \cdot n \cdot \$20,000 \tag{5}$$

[1] We need 3 ground stations because 3 bases require satellite communication, 1 base communicates with 2 satellites

### 3.4 Total/10 year cost:

The total cost for 10 years is shown below:

$$\text{Total Cost } = IC_{total} + SC + 120 \cdot MC \tag{6}$$

## 4 Results:

### 4.1 Score Function:

We calculated the total score of the network using the following function:

$$Score = \frac{\text{Total Cost}}{\$6M} + \text{Network Delay (ms)} \cdot 0.10 + \text{K-Connectedness} \tag{7}$$

### 4.2 Incurred Costs:

This section summarizes the cost breakdown of the selected network configuration.

| Parameter: | Cost ($\$M$) |
|---|---:|
| Installation: | 667 |
| Leased Monthly: | 1.9 |
| Owned Monthly: | 0.045 |
| Servers: | 0.640 |
| **Total:** | **904.720** |

### 4.3 Network Parameters:

Let $\lambda$ be the required traffic on a given node. Given a mean packet length of 20,000 bits, we calculated $\mu$ for each link as follows:

$$\mu = \frac{50\, packets}{Mb} \times \sum_{A \to B\, links} Bandwidth_{link}(Mbps) \tag{8}$$

Once we had an expression for $\lambda$ and $\mu$, we calculated the following parameters, where the "system" is the destination node:

$$Utilization = \frac{\lambda}{\mu}$$

$$E[n] = \frac{\lambda}{\mu - \lambda}$$

$$E[r] = \frac{1}{\mu - \lambda}$$

To find the end-to-end delay, we needed to account for propagation delay. We assumed that each type of link between $A \to B$ has the same utilization. Thus, the propagation delay is a weighted average

$$t_{prop} = percent_{ground} \cdot t_{ground} + percent_{satellite} \cdot t_{satellite} \tag{9}$$

For nodes involving an intelligent satellite, there is an additional $E[r]$ at the satellite. The end to end delay for a link $A \to B$ is shown below:

$$Delay_{A \to B} = t_{prop\, A \to B} + E[r]_{A \to B} \tag{10}$$

To calculate the total system response, we used a weighted average of the total network load and the load on link $A \to B$.

$$\text{Network Delay} = \sum_{allnodes} \frac{\lambda_{A \to B}}{\lambda_{network}} \cdot Delay_{A \to B} \tag{11}$$

### 4.4 Expected Results:

This section will detail the expected results on several performance parameters.
$E[r]$, the time in the system for a particular node, refers to the queue time and transmission time at a particular source. Packet Delay refers to the end-to-end delay from a packet's creation to arrival at its destination, including all queue times, service times, and propagation delays.
Table 2 shows the expected time in the system $E[r]$, by the source. To account for the various destinations from a particular source, a weighted average of a source base's traffic was utilized to calculate the expected value, $E[r]$ for each base. Table 3 shows the expected packet delay, by destination. To account for the various sources to a particular destination, a weighted average of a destination's traffic was utilized to calculate the expected value.

| **Source:** | $E[r]$ **(ms)** |
|---|---|
| Hickam | 12.7081 |
| Cheyenne | 2.9048 |
| Qatar | 3.3324 |
| Langley | 2.6059 |
| Ramstein | 6.5811 |

Table 2: Expected System Time $E[r]_{source}$

| **Destination:** | **Time (ms)** |
|---|---|
| Hickam | 91.7616 |
| Cheyenne | 33.2022 |
| Qatar | 56.8705 |
| Langley | 198.0134 |
| Ramstein | 103.3008 |

Table 3: Expected Total Delay

The total expected system time, $E[r]_{system}$ was 7.5611 ms, while the expected packet delay was 100.90 ms.
This yields the following total score:

| | |
|---|---|
| 10 Year Cost/$6M: | 150.79 |
| K-Connectedness | 0 |
| Weighted Delay: | 10.0896 |
| **Total Score:** | **160.876** |

### 4.5 Observed Results

We collected $E[r]$ at source, for each of its outbound links ($E[r$ for each source-destination pair), and we collected the total delay at each destination.
Table 4 shows the average expected delay at a given source, and Table 5 shows the average end-to-end delay at a given destination.

| **Source:** | $E[r]$ **(ms)** |
|---|---|
| Hickam | 13.2858 |
| Cheyenne | 2.9156 |
| Qatar | 3.3343 |
| Langley | 2.5908 |
| Ramstein | 6.8243 |

Table 4: Observed System Time $E[r]_{source}$

| **Destination:** | **Time (ms)** |
|---|---|
| Hickam | 91.7026 |
| Cheyenne | 33.5080 |
| Qatar | 57.4859 |
| Langley | 198.0259 |
| Ramstein | 103.3378 |

Table 5: Expected Total Delay

The system produced an average $E[r]$ of 7.839 ms, and an average end-to-end delay of 101.190 ms. These values yield the following score, given the customer's scoring function:

| | |
|---|---|
| 10 Year Cost/$6M: | 150.79 |
| K-Connectedness | 0 |
| Weighted Delay: | 10.1190 |
| **Total Score:** | **160.91** |

# 5 Analysis:

## 5.1 Traffic Load:

The following figures show the traffic loads of traffic with the given destinations. These results verify that the model accurately generates the needed traffic.

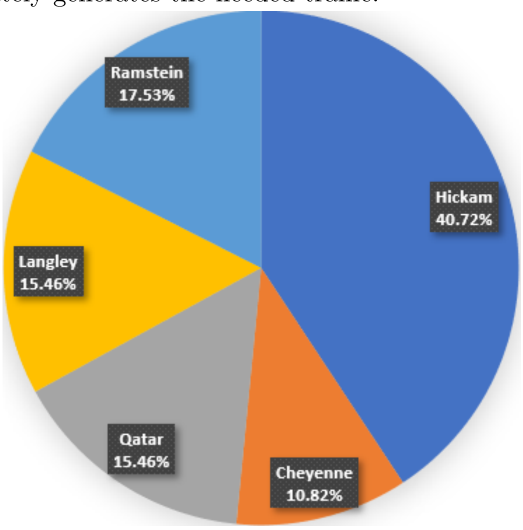


Figure 2: Expected Traffic Load

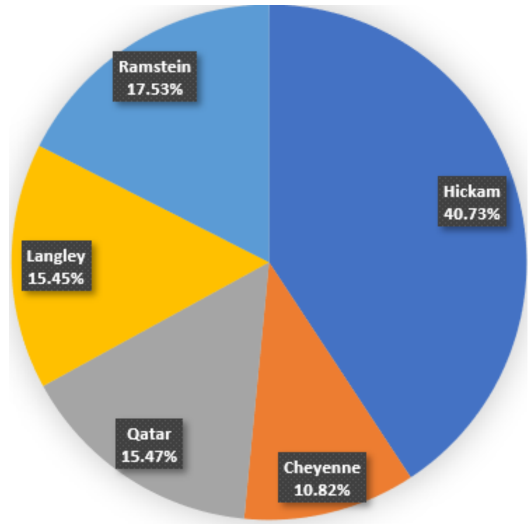


Figure 3: Observed Traffic Load

## 5.2 Mean System Response:

We observed the average system time across network, $E[r]$ to be $7.839\,ms$, a 3.68% difference from the expected value of $7.561\,ms$. This was expected due to the variation in traffic intensity in a Poisson process. There were two links which had relatively large utilizations: $Hickam \rightarrow Qatar$ had $U = 0.98$; and $Ramstein \rightarrow Cheyenne$, which had $U = 0.89$ When these links experienced bursts, the delay would increase significantly until the system returned to a steady state.

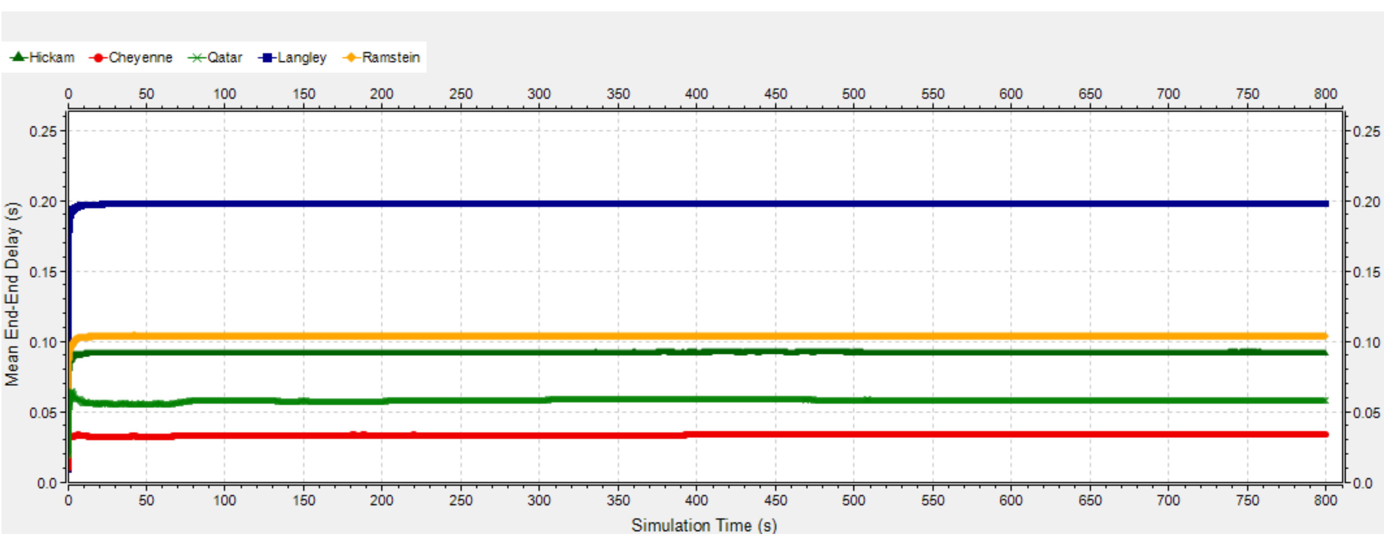


Figure 4: Total Delay by Destination

As seen in Figure 4, all destinations achieved a steady total delay. Of the five bases, packets to Langley had the worst delay of approximately 200 ms, while Cheyenne had the smallest of approximately 33.5 ms.
The total lifetime was likewise affected, with an average observed total delay of $101.19\,ms$, a 0.29% difference from the expected value of $100.90\,ms$

### 5.3 Worst Case Analysis:

The average delay observed matched the expected delay. However, this does not account for the increased variance and increased times caused by bursts. Tables 6 and 7 show the worst-case time in system, $E[r]$, for each source; as well as the worst-case total delay for each destination.

| **Source:** | $E[r]$ **(ms)** |
|---|---|
| Hickam | 168.9815 |
| Cheyenne | 63.7588 |
| Qatar | 57.0325 |
| Langley | 49.7708 |
| Ramstein | 522.9085 |

Table 6: Worst Case System Time, $E[r]_{source}$

| **Destination:** | **Time (ms)** |
|---|---|
| Hickam | 265.725 |
| Cheyenne | 550.238 |
| Qatar | 215.651 |
| Langley | 277.647 |
| Ramstein | 270.018 |

Table 7: Worst Case Total Delay

As seen in Tables 6 and 7, the links accounting for the worst delay is the link going from $Ramstein \rightarrow Cheyenne$. To illustrate the source of this worst-case delay, the $Ramstein \rightarrow Cheyenne$ link delay is broken down below.[2]

| Timing Component | Time (ms) | Percentage |
|---|---|---|
| Queue Time | 516.73 | 93.90 |
| Transmission Time | 6.21 | 1.13 |
| Propagation Delay | 27.33 | 4.97 |
| Total Delay | 550.27 | 100 |

Table 8: Timing Breakdown of Worst-Case Link

As shown in Table 8, 93.9% of the worst-case delay was avoidable, incurred while the packet was waiting in the queue, with a queue length of 113 packets.
By decreasing the link's utilization, the maximum delay can be decreased significantly. How to alleviate this delay will be addressed in Section 5.5 Bottleneck Analysis.

### 5.4 Buffer Recommendations:

The first network recommendation would the buffer size of each server. Although during simulation, each node had an infinite transmitting and receiving buffer capacity, we recommend a 1MB transmission buffer at each node. We do not need to consider a receiving buffer as each packet sent is point to point. Therefore, when a packet is received at a node, it has reached its destination and does not need to be buffered. When determining the appropriate transmission buffer size, we used the max queue length of each node to decide. The max transmitting queue lengths experienced during the simulations for each source is shown below in Table 9
Hickam experienced the largest max queue length at 412 packets. For a buffer to hold 412 packets with a mean size of 20,000 bits, we calculated the size needed using the equation below:

$$\frac{412\,packets}{1\,buffer} \times \frac{20,000\,bits}{1\,packet} \times \frac{1\,byte}{8\,bits} \times \frac{1\,MB}{1024^2\,bytes} = 0.982\,MB \tag{12}$$

[2]The times are slightly different than the tables above due to rounding

| Source: | Max Queue Length |
|---|---|
| Hickam | 412 |
| Cheyenne | 30 |
| Qatar | 28 |
| Langley | 30 |
| Ramstein | 113 |

Table 9: Max Queue Lengths(packets)

To minimize packet loss across the network based on the buffer size needed to hold the maximum experienced queue length at a node, we recommend using a 1MB transmission buffer. Because all nodes use the same server and a 1MB buffer is relatively cheap, each server used in the network will have a 1MB transmission buffer

### 5.5 Bottleneck Analysis

There existed two bottleneck links in our network: Hickam → Qatar and Ramstein → Cheyenne. As discussed in Section 5.4, the Hickam → Qatar link experienced the greatest max queue length at 412 packets, whereas Ramstein → Cheyenne experienced the worst end to end delay of 550.238 ms. To alleviate these bottlenecks and decrease their utilization there are two possible solutions. We could increase the bandwidth by adding a new link or upgrading an existing to link. Although by increasing the bandwidth, we guarantee a decrease in utilization and a corresponding decrease in system delay, we also incur an additional cost for the additional bandwidth. A second solution would be to route a portion of the bottleneck solution through alternate routes, utilizing existing infrastructure. This solution would incur no additional cost. While this would reduce the utilization on the bottleneck links, there would be impacts on the other link's delays, queue lengths, and utilizations that may have adverse impacts on the system's performance as a whole.

## 6 Conclusion: