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:

The write up for Project 4 is broken up into six sections. The introduction provides an overview of the work completed and the analysis performed. Methodology goes into detail on how the group designed a process to build and optimize a cost-effective network. Cost outlines how the group calculated cost of the network and captures cost nuances in the problem statement. Results discusses how the network solution scores in accordance with the provided scoring formula and how the inputs to this formula are generated. The results section also discusses the observed results from the simulated network. The analysis section provides commentary on the observed results to include findings that confirm our initial analytical assumptions and samples of worst-case scenarios in the network. The team's final thoughts are captured in the conclusion.

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 ≈ 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 Traffic Load:

2 Methodology:

2.1 Scoping Process:

During the scoping process an Excel spreadsheet was built wherein we could designate links in the networks; and the spreadsheet would generate the total cost of the network, the average delay in the network, and k-connectedness. From here we could calculate the score of the network and âplayâ with link allocations and directly see the impact. During this phase two important observations were made. The first was that each link is a full-duplex channel. Due to this stipulation either node connected by a link has access to the full capacity of the link. This would have implications during the optimization process as we would only need to optimize for the link direction that has the highest load because the reverse direction would have a smaller utilization. The second observation was that cost heavily influences the score of the network. This fact drives many decisions during the optimization process to cut cost at the sacrifice of overall network delay or k-connectedness.

2.2 Optimization Process:

The optimization process consisted of two stages: automated optimization and then hand optimization. The Excel Solver tool was used optimize the spreadsheet in reference to the network score. While this tool would in fact find a value, it was dubious whether it was truly the most optimized score. Upon inspection we found that the solver would occasionally select multiple of one specific link type when it could have have selected a higher bandwidth link for cheaper. These types of discrepancies lead us to believe that the solver would only solve to a local minimum for some values. From here we would need to hand optimize the network to keep lowering the score.
During hand optimization the six rules of thumb listed below were applied to decisions to change the link configuration between any two nodes:

1. Cost is the most significant driving factor in score.

2. Due to full-duplex communications both directions of link see full link capacity.
3. Use as few links as possible to minimize server costs.
4. Use free intelligence satellites when able.
5. Use satellite communication only if total fiber cost per month is greater than satellite communication cost per month.
6. Use leased fiber if total fiber cost per month is greater than leased fiber cost per month.

Using these rules, we were able to generated an optimal 4-connected network topology depicted in Figure 1.
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 ≈ 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.

2.3 Network Topology:

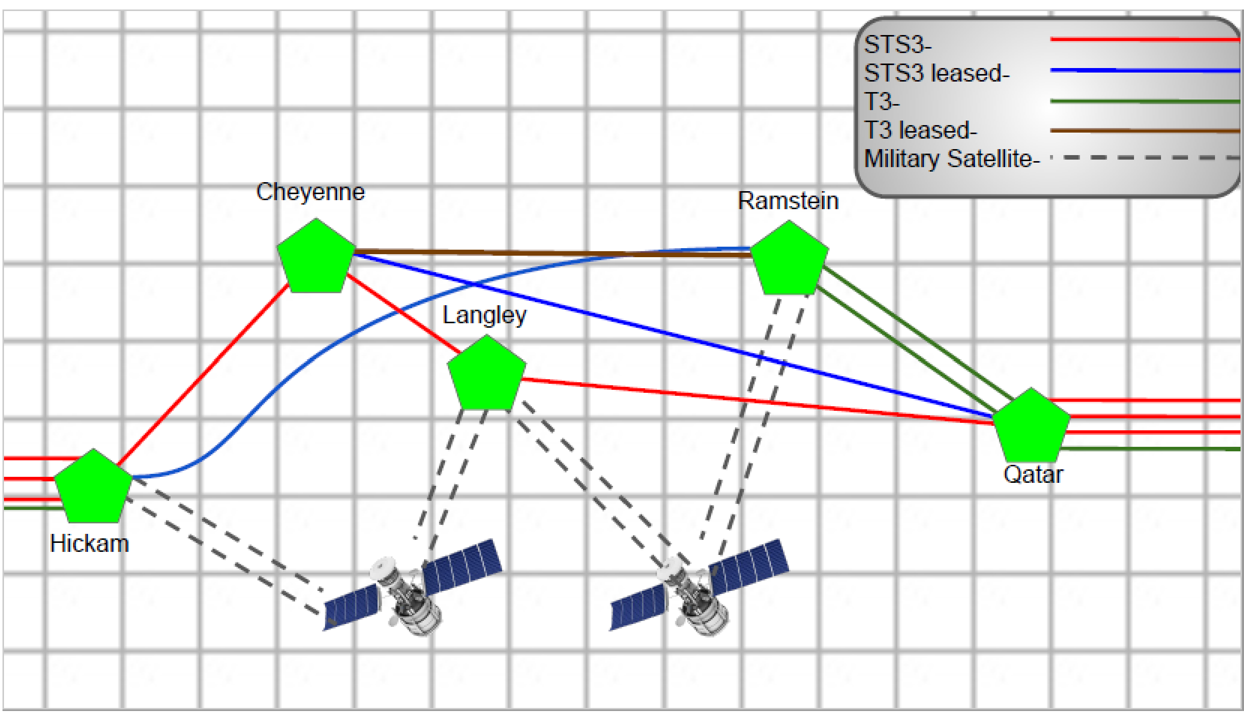

Figure 1: Network Topology of Routing Network

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

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

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:

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

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

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 λ be the required traffic on a given node. Given a mean packet length of 20,000 bits, we calculated μ 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 λ and μ, 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 1 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 2 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 1: 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 2: 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 3 shows the average expected delay at a given source, and Table 4 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 3: 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 4: 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:

Table 5 shows the expected traffic load, per source, in packets per second.

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 5: Traffic Load by Source

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

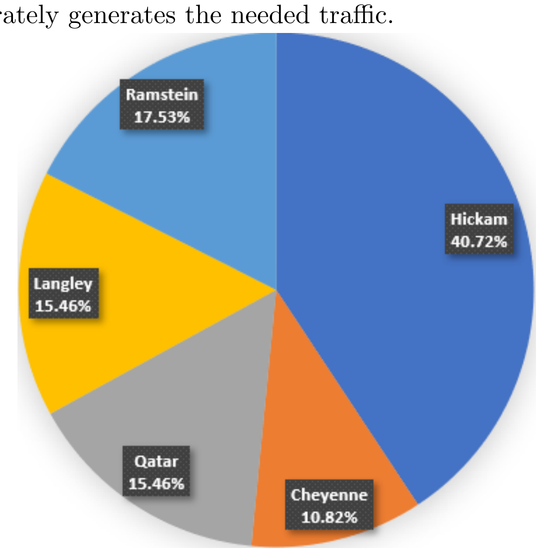

Figure 2: Expected Traffic Load

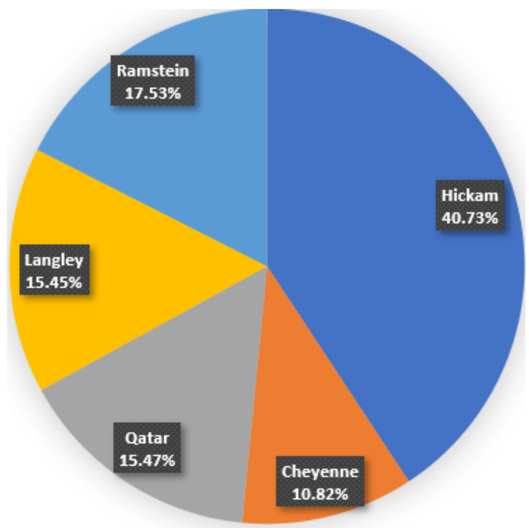

Figure 3: Observed Traffic Load

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.

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 $100.90\,ms$

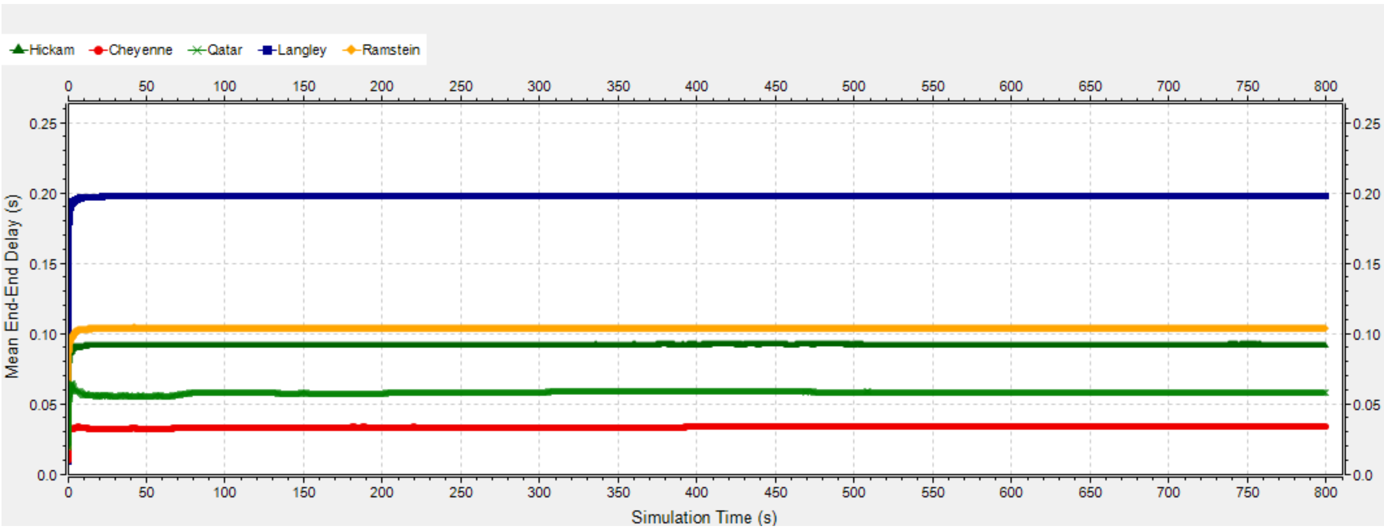

Figure 4: Total Delay by Destination

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.

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

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

Source:	**Max Queue Length(packets)**
Hickam	412
Cheyenne	30
Qatar	28
Langley	30
Ramstein	113

Table 9: Max Queue Lengths

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:

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

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:

For this experiment, our team was tasked to design a communication system model for 5 geographically separated transmission nodes and then simulate our design in OMNeT++ to analyze our design. Our network was to be evaluated based on a cost function that was comprised of the total 10 year cost, the k-connectedness of our network, and the average end-to-end delay. The lower the value from the cost function, the better the evaluation of our network from our customer. To optimize our network for a low value, our team first set off to create a 4-connected topology which connected every link point-to-point. From there, we began to optimize cost/average delay for the highest throughput for a given link due to the full-duplex communication links being used. Once the final configuration had been determined, we then calculated the expected results that our network should produce based on our design. We determined that the total 10 year cost would be $904.720M, the average end to end delay would be 101.190ms and that our network was 4-connected producing an expected total score of 160.91. Our team then simulated our design using OMNeT++ to both validate and verify our proposed network. Our simulation showed that the expected traffic loads matched the observed verifying that we had indeed picked the correct model. Furthermore, our simulation produced an average total delay of 101.19ms which is only a 0.29% difference from the expected value of 100.90ms validating our implementation of the network. Given the customer's scoring function, our team's final network configuration would yield a total score of 160.91.

Appendix A: Tables

Destination	Load (pps)	Percent:
Hickam	1000	10.31%
Cheyenne	1400	14.43%
Qatar	3750	38.66%
Langley	2750	28.35%
Ramstein	800	8.25%
Total:	**9700**	**100.00%**

Table 10: Expected Traffic Load by Destination

Destination	Count (packets)	Percent:
Hickam	2399398	10.31%
Cheyenne	3360045	14.43%
Qatar	8997408	38.66%
Langley	6601509	28.36%
Ramstein	1922210	8.26%
Total:	23280570	**100.00%**

Table 11: Observed Traffic Load by Destination

The following tables show the max and mean queue length and time, for each source node. Note, each source has a link to each destination, which accounts for the small mean queue length, relative to the maximum.

Source	Max	Mean
Hickam	412	13.64
Cheyenne	30	1.26
Qatar	28	1.75
Langley	30	1.47
Ramstein	113	3.39

Table 12: Observed Queue Length

Source	Max (ms)	Mean (ms)
Hickam	168.52	5.36
Cheyenne	56.68	1.22
Qatar	54.64	1.89
Langley	49.24	1.19
Ramstein	516.73	10.92

Table 13: Observed Queue Time

The following table shows the max and mean times at a given source node, accounting for both queue and service time:

Source	Max (ms)	Mean (ms)
Hickam	168.98	6.23
Cheyenne	63.76	3.30
Qatar	57.03	3.19
Langley	49.77	2.09
Ramstein	522.91	13.05

Table 14: Observed Nodetime