Effect of Dynamic Topology on Circuit and Packet-Switched Satellite Networks

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Abstract—Since next-generation satellites are being designed to be network-centric, with routers and switches on board, the choice being circuit and packet switching (or combination of both) has become a crucial technology decision that many designers of satellite networks must grapple with. Of particular importance is how each type of switching responds to dynamic changes in network topology. The following simulation study characterizes and quantifies how circuit and packet-switched satellite networks respond to both planned and unplanned changes in network topology. Results show that circuit-switched satellite networks, which must teardown and reestablish connections, are less robust in handling dynamic changes in network topology.12

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1. MOTIVATION

Previous generations of military space networks mainly used satellites with transponders (i.e. “bent pipes”) that were divorced from networking considerations. Next-generation satellites are being designed to be network-centric, with routers and switches on-board, making networking considerations a crucial part of the payload design. Thus, the choice between packet switching, circuit switching, or a combination of both has become a major technology decision that many designers of military satellite networks must grapple with.

Choosing between packet and circuit switching, however, involves many considerations. There are a large number of interrelated issues and determining which are drivers can be difficult. This paper addresses one major consideration, namely, how packet and circuit-switched networks respond to dynamic network topology. Typically, packet vs. circuit switching studies focus on their relative throughput. In this study, the relative flexibility (and the quantitative consequences) of circuit- and packet-switched systems in dynamic link conditions is addressed. For the purposes of this paper, dynamic topology includes broken links, changing links between node pairs, or changes in link lengths when node pairing stays the same.

In many satellite constellations, the wireless links between satellites and ground stations can show all types of dynamic link conditions. These changes may be planned, as the result of satellite nodes having non-geosynchronous (GEO) orbits and moving relative to ground stations and other satellites in the constellation. They may also be unplanned, as the result of catastrophic failures or unexpected channel disturbances such as fading or jamming. These topology changes often result in an increase or decrease in the path length (and error-rate) between nodes and can cause network links to be made or broken. Further, these changes could have huge implications for the routing of network traffic and it therefore is crucial to understand how each switching technology responds.

In order to adjust to planned topology changes, packet switched systems can update routing tables for each node and reroute packets immediately. Although optimal routing may require global routing table changes, local changes are all that are required to deliver the packets to their destination. Circuit switched systems are much less flexible. In a circuit switched system, any planned change in topology requires the current circuit to be torn down and a new circuit to be established. This can be done in one of two ways. A circuit using the new route can be established prior to tearing down the old circuit. This allows an immediate transition from the old to new route, but for the time both circuits are up, is wasteful of the network’s (bandwidth) resources. The second method requires the old circuit to be disconnected before establishing the new circuit. This preserves the network’s resources but results in a fixed time where the connection is idle, i.e. no circuits are set-up and no data can be sent.

Circuit switched systems are also less flexible in handling unplanned link outages. If an unplanned link break occurs, both packet and circuit-switched systems must be able to detect this breakage and adjust their routing accordingly. During the time the system is adjusting to the unplanned breakage, all data is delayed or lost. For packet switching, this adjustment can be done at the local (node) level. For

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2 IEEEAC paper #1058, Version 1, Updated October 27, 2004
circuit switching, all elements of the circuit must be contacted so the broken circuit can be properly disconnected and the new call established. Having to contact all elements of the circuit and re-establish a new call results in an increase in the amount of data that is delayed or lost.

The following simulation study characterizes and quantifies how circuit and packet-switched satellite networks respond to both planned and unplanned changes in network topology. This study is part of a series that presents the trades, quantities, and quantitative methods associated with evaluating packet and circuit switching systems so satellite communications personnel can make better decisions when designing their networks. These studies are generic rather than specific to a particular system in order to illustrate fundamental principles and have a wide applicability.

The network simulations in this study are run using the Beowulf Network Evaluation Tool (BeoNET), developed in-house at The Aerospace Corporation. BeoNET is designed to take advantage of cost-effective parallel-computing technologies and address the specific issues of space networks. It includes a user-end problem definition subsystem that runs on desktop PCs and a run-time subsystem that runs on a Beowulf cluster, consisting of hundreds of processors connected via a high-speed, dedicated local area network.

2. PLANNED TOPOLOGY CHANGES

Planned Topology Change: System and Scenario

To model planned routing changes, we have chosen a network where there are two ground stations communicating via a 10-Ball satellite constellation, as shown in Figure 1.

![Figure 1 – Planned Topology Change: System and Scenario](image)

| Ground Station 1 | Ground Station 2 |
|------------------|------------------|
| **Optimal Path from 0 – 600 sec** | **Optimal Path from (600+ sec)** |

Data from nine users (each with a 135 kbps data rate) are sent from ground station 1 to ground station 2 across a 2.7 Mbps link. Data traveling across both the packet-switched and circuit switched networks, comes in segments with inter-release times (i.e. intervals between packet transmissions) that are exponentially distributed. From 0 to 600 seconds, both packet and circuit switched data is routed from ground station 1 to ground station 2 via satellites 5, 4, and 7 as shown by the dashed, red arrows. At 600 seconds, ground station 1 becomes connected to satellite 8, and the optimal path changes to that denoted by the solid, green arrows. The optimal path change may be due to a link break in the pre-600 second path or because the total path distance changed due to the stretching and contracting of link lengths. These or other factors are relevant depending on which routing algorithm is in effect.

Since packet switching systems are able to dynamically change their routing, no special configurations are required and at 600 seconds, packets are immediately rerouted from the dashed-red to the solid-green path.

For circuit switching, there are a variety of pre-planned strategies that can be used to make the routing change at 600 seconds. One approach would be shut down some of the existing circuits (along the current path), while the new circuits (along the new path) are being established. This strategy, however, results in a fixed time where some of the data cannot be sent. The approach taken here is to set aside some additional bandwidth so that the new circuits can be set-up while the old circuits are still operating.

Specifically, three different strategies are considered that implement the three circuit configurations shown in Figure 2. Circuit configuration 1 contains ten circuits that have a bandwidth of 270 Mbps each. Nine of the circuits are for the current user traffic, with one spare circuit to establish an alternate route. To make the routing change, each user must be switched over on a one-by-one basis. The sequence of events is as follows. At 600 seconds, the single spare circuit establishes a connection along the alternate path. Once that circuit is established, the traffic from the first user can be switched over the new path, and the old circuit carrying the first user’s traffic can be torn down. Once that circuit is torn down, a new circuit along the alternate path can be established to carry the second user’s traffic. This one-by-one handoff occurs until all nine users have switched over their circuits.

Circuit configuration 2 contains twelve total circuits, with three spare circuits to establish an alternate route. To make the routing change, circuits in configuration 2 can be switched over three at a time. However, to allow for three spare circuits, the total bandwidth for each circuit must be reduced to 225 kbps. Finally, configuration 3 contains eighteen total circuits, with nine spare circuits to establish an alternate route. To make the routing change, circuits in configuration 3 can all be switched over at once. However,
to allow for nine spare circuits, the total bandwidth for each circuit must be reduced to 150 kbps.

\[ 2.7 \text{ Mbps} \]

Configuration 1

\[ 10 \text{ Ckts (270 kbps)} \]

Configuration 2

\[ 12 \text{ Ckts (225 kbps)} \]

Configuration 3

\[ 18 \text{ Ckts (150 kbps)} \]

Circuits for Current Route

Circuits Reserved for Alternate Route

**Figure 2 - Circuit Switching Configurations for the Planned Topology Change**

**Planned Topology Change: Results**

The latency response for the packet-switching system is shown in Figure 3. This and the following results are for a Poisson traffic distribution which experiences statistical multiplexing benefits in queued network systems. Although many traffic flows exhibit long-range dependent (commonly called self-similar) distributions, statistical multiplexing benefits are always apparent to a greater or lesser degree.

**Figure 3 - Packet-Switching End-to-End Latency After a Planned Topology Change**

Here the end-to-end latency for users 1, 5, and 9 is plotted as function of the data-release time. At 600 seconds, when the optimal route changes, the data from all users are almost immediately switched over to the more optimal route. Both before and after the routing change, there is a small variation in the end-to-end latencies for all users. This is because all users share the same bandwidth and can take advantage of statistical multiplexing. Specifically, the minimum latency and standard deviation of the data sent prior to the routing change is 244 and 1.5 ms. The minimum latency and standard deviation of the data sent after the routing change are 221 and 1.5 ms respectively.

**Figure 4 - Circuit Switching End-to-End Latency for a Planned Topology Change (Configuration 1)**

Again the end-to-end latency for users 1, 5, and 9 is plotted as function of the data-release time. Unlike packet switching, the data for circuits cannot be switched over immediately to the optimal route. In accordance with the strategy described above, the data for user 1 is switched over first, followed by user 5 and then user 9. Because there are nine circuits to switch over, the total circuit transition time is 7.83 seconds. In addition, the minimum latency and standard deviation is larger for circuit configuration 1 than for the packet switching (both before and after the optimal route is switched). Specifically, the minimum latency and standard deviation of the data sent prior to the routing change are 263 and 16.95 ms, respectively. The minimum latency and standard deviation of the data sent after the routing change are 240 and 16.4 ms, respectively. These latencies are higher than those for packet switching because circuit switching cannot take advantage of statistical multiplexing. For the packet-switching network, all 9 bursty users are averaged together. This tends to smooth out the burstiness of the traffic. For the circuit switching users, each user sends data across its own portion of the bandwidth and is, therefore, more susceptible to bursts in traffic.

**Figure 5 - Circuit Switching End-to-End Latency for a Planned Topology Change (Configuration 2)**

Figure 5 plots the latency response for circuit configuration 2.
Figure 5 - Circuit Switching End-to-End Latency for a Planned Topology Change (Configuration 2)

Once again the data for user 1 is switched over first, followed by user 5, and finally user 9. However, now the transition time to change over all the circuits has been reduced to 2.29 seconds. This is because for configuration 2, three circuits can be changed over at a time instead of one. The minimum latency and standard deviation, however, are slightly greater than those for circuit configuration 1 (both before and after the routing change). Before the routing change, the minimum latency and standard deviation of the data sent are 267 and 28.3 ms, respectively. After the routing change, the minimum latency and standard deviation of the data sent are 244 and 26.1 ms, respectively. These latencies are higher than those for circuit configuration 1 because the size of each circuit has been reduced from 270 Mbps to 225 Mbps, and the circuits for configuration 2 are forced to operate at a slightly higher utilization.

Figure 6 plots the latency response for circuit configuration 3.

For configuration 3, all circuits can be switched over at once and thus, the circuit transition time is only 0.44 seconds. However, the minimum latency and standard deviation for all users is greatly increased. Before the routing change, the minimum latency and standard deviation are 280 and 220 ms, respectively. After the routing change, the minimum latency and standard deviation are 258 and 191.3 ms, respectively. These latencies are the highest of all circuit configurations because for circuit configuration 3, each circuit is only 150 Mbps and must operate at 135/150 = 90% capacity. Bursty traffic being transmitted at 90% capacity, is subject to large queuing delays. In fact, the data for user 1 shows these delays can become extremely high, before they settle back down. Clearly, configuration 3 is not a desirable design.

The latency responses for packet switching and all three cases of circuit switching are summarized in Figure 7 and Figure 8. Figure 7 plots the end-to-end latency distributions for all switching cases, calculated both before and after the routing change. Prior to the routing change, the packet switching network has the smallest average latency and the narrowest distribution, followed by circuit configurations 1, 2, and 3. The difference in the latency distributions between packet switching and circuit configuration 1 is primarily due to statistical multiplexing. Both operate at similar channel utilizations; 9*135 kbps / 2.7 Mbps = 45% for packet switching and 135 kbps / 270 kbps = 50% for circuit configuration. For packet switching, however, all 9 bursty users are statistically averaged together, while for circuit configuration 1 they are not. The difference in the distributions for circuit configurations 1, 2, and 3 is due to the difference in circuit size for each configuration. While circuit configuration 1 operates at 50% utilization, circuit configuration 2 operates at 135 kbps/225 kbps = 60% utilization, and circuit configuration 3 operates at 135 kbps/150 kbps = 90% utilization. For bursty traffic, higher utilizations can result in much larger and more variable queuing delays. After the routing change, the distributions for packet and circuit switching show a similar behavior, except now all curves have been shifted to the left to account for the new, more optimal, path.
Figure 7 - Latency Distributions for a Planned Topology Change

Figure 8 illustrates one of the main tradeoffs that must be considered when designing a packet or circuit-switching system to handle planned routing changes. In this figure, the minimum end-to-end latency (after the routing change) is plotted for each case as a function of route transition time. The standard deviation for latency (or jitter) is denoted by the vertical error bars. As a network designer, you would like to minimize latency, jitter, and route transition time. Packet-switching is clearly the optimal choice here, with a route transition time of essentially 0, a minimum latency of 221 ms, and a jitter of only 1.5 ms. For circuit-switching systems, a trade must be made between route-transition time and minimum latency/jitter. Circuit configuration 1 has the longest route-transition time but the smallest minimum latency and jitter (for the circuit switching cases). Circuit configuration 3 has the shortest transition time but the largest latency and jitter. A compromise between both extremes would be circuit configuration 2.

Figure 8 - Minimum Latency vs. Route Transition Time for a Planned Topology Change

The results of Figure 8 show that circuit-switching designers are forced to choose between a fast route transition time and a high latency/jitter (configuration 3) or a slow route transition time and a lower latency/jitter (configuration 1). Packet-switched systems, on the other hand, are able to achieve both fast transition times and low latencies/jitter, essentially giving the best of both worlds.

3. UNPLANNED TOPOLOGY CHANGES

Unplanned Topology Change: System and Scenario

To study unplanned topology changes, we again choose a scenario where there are two ground stations communicating via a 10-Ball satellite constellation, as shown in Figure 9.

Figure 9 - Unplanned Topology Change: System and Scenario
Data from a single user is sent from ground station 1 to ground station 2 across a 2 Mbps channel at a rate of 1 Mbps. Data traveling across both the packet-switched and circuit-switched networks, comes in segments with inter-release times that are exponentially distributed. From 0 to 360 seconds, both packet and circuit switched data is routed from ground station 1 to ground station 2 via satellites 5, 4, and 7 as shown by the red arrows. An unplanned link break occurs between satellites 4 and 7 at exactly 360 seconds. Note that the time of the unplanned link break was chosen arbitrarily and was not meant to correspond to the planned topology change described in the previous section.

For the packet switched system, all data traveling between satellites 4 and 7 at the time of the link break are lost. Satellite 4 immediately detects the link break, sends a message to notify satellite 5 and ground station 1, and reroutes data through satellite 9 (shown by the blue arrows). At 360.13 seconds, ground station 1 receives the link break message from satellite 4, and reroutes data along the new optimal path, as shown by the green arrows.

For the circuit switched system, satellite 4 also detects the link break and sends a message back to ground station 1 but is unable to reroute the data. Until ground station 1 receives the link break message at time 360.13 seconds, and the current circuit is torn down, all data continues to be sent across the original circuit and gets lost. When ground station 1 receives the link break, the current circuit is torn down and a new circuit is established along the new optimal path, as shown by the green arrows. While the new circuit is being established, all data coming from ground station 1 is put in a queue. Once the new circuit is established all queued data can be sent to ground station 2.

Unplanned Topology Change: Results

For the packet-switched system, all data traveling between satellites 4 and 7 at the time of the link break are lost. Satellite 4 immediately detects the link break, sends a message to notify satellite 5 and ground station 1, and reroutes data through satellite 9 (shown by the dashed blue arrows). At 360.13 seconds, ground station 1 receives the link break message from satellite 4, and reroutes data along the new optimal path, as shown by the dotted green arrows.

For the circuit switched system, satellite 4 also detects the link break and sends a message back to ground station 1 but is unable to reroute the data. Until ground station 1 receives the link break message at time 360.13 seconds, and the current circuit is torn down, all data continues to be sent across the original circuit and are lost. When ground station 1 receives the link break, the current circuit is torn down and a new circuit is established along the new path, as shown by the dotted green arrows. While the new circuit is being established, all data coming from ground station 1 is put in a queue. Once the new circuit is established all queued data can be sent to ground station 2. Figure 10 plots the end-to-end latency as a function of time for both packet and circuit switching. It provides a good summary of how both networks respond to unplanned link outages.

Up to the point of the link break, packet and circuit-switched data travels along the optimal (solid red) path with an end-to-end latency of about 225 ms. When the link break occurs at 360 seconds, both the packet and circuit-switched data released during time period A are in transit between satellites 4 and 7 and get dropped. The packet-switched data released during time period B are rerouted along the intermediate (sub-optimal) path and arrive at the destination with an end-to-end latency of around 290 ms. The circuit-switched data, on the other hand, continue to travel down the original circuit and get dropped at the point of the link break. At the beginning of time period C, ground station 1 is notified of the link break. The packet-switched data are immediately routed along the new optimal path and arrive at the destination with a latency of around 250 ms. The circuit-switched data, on the other hand, are queued while the new circuit is being set-up (along the new-optimal path). During time period C, the new-circuit is eventually set-up and the data queue is eventually emptied until the latency of the circuit-switched data approaches that of the packet switched data.

The amount of lost data for both types of switching is shown in Figure 11. For the data rate of 1 Mbps, the packet-switching system loses about 7 kB of data while the circuit switching system loses almost 36 kB of data. Note that the ratio of lost data for packet vs. circuit switching should approximately equal the ratio of time that each type of

![Figure 10 – End to End Latency for an Unplanned Topology Change](image-url)
switching spends sending data to the broken link (i.e. A/A+B).

![Figure 11 - Unplanned Topology Change: Amount of Lost Data](image)

4. CONCLUSION

The results of this study show that circuit switched systems are less robust in handling dynamic network topology, no matter whether these changes are planned or unplanned. For planned topology changes, packet switched systems can automatically change routing without setting aside any spare bandwidth or incurring additional delay. In order for circuit-switched systems to implement routing changes, they must set aside spare bandwidth and incur additional delays due to the set-up and teardown of circuits.

For unplanned link outages, packet-switched systems can detect the break and adjust routing locally. Circuit switched systems, on the other hand, must contact every element of the circuit in order to properly change their configuration. The more time that’s spent detecting the link breakage and establishing a new circuit, the larger the amount of dropped and delayed data. Circuit switched systems can establish redundant circuits, with alternate paths, that can be activated as soon as a link breakage has been detected. This, of course wastes bandwidth but eliminates the queuing time needed while the new circuit is being established. A redundant circuit, however, will not reduce the amount of data lost while each element of the circuit is being informed of the link outage.

REFERENCES

NONE

BIOGRAFÍA

James Hant recibió una B.S. en Biomedicina y ingeniería de la Universidad de California, en San Diego (UCSD) en 1993 y M.S. y Ph.D. en Electrónica y Ingeniería de la Universidad de California, en Los Ángeles (UCLA) en 1996 y 2000, respectivamente. Desde junio de 2000 hasta junio de 2001, él fue un ingeniero de software de sistemas en Conexant Systems en Newport Beach, CA., diseñando y implementando software de reconocimiento de voz para aplicaciones de internet. Desde junio de 2001, él ha sido miembro de la técnica del personal en The Aerospace Corporation en El Segundo, CA, donde ha trabajado en la simulación, modelado, y diseño de sistemas de comunicación satelital. La investigación de interés de Dr. Hant incluyen el diseño de redes satelitales, comunicación de canal y diseño de satélite.

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