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NETWORKS FOR AUTONOMOUS FORMATION FLYING SATELLITE SYSTEMS[1]

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ABSTRACT

The performance of three communications networks to support autonomous multi-spacecraft formation flying systems is presented. All systems are comprised of a ten-satellite formation arranged in a star topology, with one of the satellites designated as the central or "mother ship." All data is routed through the mother ship to the terrestrial network. The first system uses a TCP/IP over ATM protocol architecture within the formation; the second system uses the IEEE 802.11 protocol architecture within the formation; and the last system uses both of the previous architectures with a constellation of geosynchronous satellites serving as an intermediate point-of-contact between the formation and the terrestrial network. The simulations consist of file transfers using either the File Transfer Protocol (FTP) or the Simple Automatic File Exchange (SAFE) Protocol. The results compare the IP queuing delay, and IP processing delay at the mother ship as well as application-level round-trip time for both systems. In all cases, using IEEE 802.11 within the formation yields less delay. Also, the throughput exhibited by SAFE is better than FTP.

INTRODUCTION

Multi-spacecraft formation flying systems enable an improvement in mission performance while reducing operating costs [1]. These systems are comprised of multi-satellite fleets and their associated ground stations, which together achieve the following objectives. First, satellites in the same formation can provide redundancy in the event of a node failure. Second, multiple satellites in a formation can be used to increase the overall system capacity and throughput, and finally, multiple satellites in a formation enable larger spatial coverage as well as prolonged temporal availability. It is anticipated that the use of autonomous multi-satellite formation flying systems will be cost-effective to implement and more reliable than single-satellite counterparts [2][3].

Current research on the concept of autonomous formation flying satellite systems emphasizes the techniques necessary to perform control of formation location and geometry, which is accomplished with the exchange of command, control, and navigation information between spacecrafts in the formation. Researchers at Stanford University have demonstrated the effective use of Carrier-Phase Differential GPS (CDGPS) to obtain very precise (cm level) estimations of formation location and relative geometry [4]. Additionally, several other papers have been published in the literature concerning the precise control of the spacecrafts within a multi-satellite formation. The literature indicates that the distances between the satellites in a formation should be controlled to within a centimeter in the near-term, i.e., the next five years, and to within a fraction of a centimeter for missions in the next ten years. The Autonomous Formation Flyer (AFF) Sensor, for example, borrows technology from the Global Positioning System (GPS) to maintain the precise control of the spacecraft within the Deep Space 3 (DS3) mission [5]. Similarly, a Collective Intelligence (COIN) has been devised to control the constellations of communications satellites [6]. From reviewing the literature, it is clear that the precise control of the spacecraft within a formation flying system is very important for several planned missions, and the degree of precision is a function of the intended mission.

While a mechanism to perform formation control and navigation is necessary, a suitable inter-spacecraft communications system (ISC) is necessary to support the exchange of command, control, and navigation information as well as scientific data. The ISC system must also support formation adaptation to dynamic mission conditions [7].

In order for formation flying satellites to accomplish a greater level of autonomy, future missions will require the spacecrafts within the formation to exhibit a higher level of functionality. This functionality can be accomplished by incorporating the Internet Protocol (IP) into the protocol architecture that is utilized by each spacecraft within the formation. Incorporating IP into the ISC system provides several advantages, some of which include the following. IP allows the infusion of commercially developed. technology, and provides interoperability with the terrestrial Internet. Also, IP could provide multicasting and broadcasting capabilities, which may prove useful for missions involving satellites in formation flight.

This paper presents the simulated performance analysis of three networks to support the inter-spacecraft communication needs for autonomous multi-spacecraft formation flying systems. As mentioned, an important objective of this research is to investigate the concept of "Internet node in the sky" as it applies to formation flying satellite systems. Therefore, from a networking perspective, the formation flying system has to be interoperable with the terrestrial Internet. The basic simulated protocol architecture is TCP/IP over ATM. The first system uses a TCP/IP over ATM protocol architecture within the formation; the second system uses the IEEE 802.11 protocol for communication within the formation; and the last system uses both of the previous architectures with a constellation of geosynchronous satellites serving as an intermediate point-of-contact between the formation and the terrestrial network. The performance of the three systems is compared for some representative file transfers using either FTP or SAFE.

SAFE PROTOCOL

The SAFE protocol operates in the application layer of the protocol suite and was designed to function independently of the underlying transport protocol. Therefore SAFE can use UDP, rather than TCP, as the transport protocol [8]. Since UDP is insensitive to propagation delays, SAFE avoids the well-documented problems associated with using TCP over satellite links. Additionally, SAFE does not waste any time establishing a connection, since UDP is connection-less. However, UDP does not provide flow control, reliable transfer of data and congestion control; therefore, SAFE must provide these services in the application layer.

The File Transfer Protocol (FTP) from the TCP/IP suite provides a service comparable to SAFE, but FTP must be used in conjunction with TCP. SAFE, as mentioned, is not bound to any particular transport protocol since all the reliability, flow control and congestion control mechanisms are provided in the application layer. As a result, SAFE can take advantage of the changes (such as the

CCSDS-SCPS suite) that are being devised to improve network performance over satellite and space communication links.

SAFE uses the client-server network configuration where the server node hosts the source data, called the primary file, and the client attempts to create a secondary file which is an exact replica of the primary file. The client sends requests to the server, and the server passively waits for a request to arrive from the client; the request initiates the transfer from the server to the client. If a request from the client extends beyond the end of the primary file, the server will set an end-of-file (EOF) flag within the reply packet. When the client detects the EOF flag, it will wait a prescribed period of time before requesting additional data beyond the last advertised EOF offset. Since the client periodically sends requests for more data, the secondary file at the client is an exact replica of the primary file.

As mentioned earlier, since SAFE operates in the application layer and uses UDP as the transport protocol, the SAFE protocol must provide the functions of TCP. The flow control, reliable data transfer and congestion control mechanisms used by SAFE are very similar to that of TCP Reno, and it implements the slow start, congestion avoidance, fast retransmit and fast recovery algorithms of TCP. In order to maximize the utilization of network bandwidth, SAFE sends requests asynchronously in that multiple requests can be outstanding at any time. To correlate the pending requests with the received segments, the SAFE client associates a message ID to each request that is sent to the SAFE server, and the server will return this message ID within the reply packet. Thus, the client can match requests to replies and reorder the segments, if necessary, before writing the data to the secondary file.

NETWORK CONFIGURATION I

The topology of the first formation flying simulation scenario is shown in figure 1. In this configuration, we consider a formation flying system consisting of ten satellites. These satellites are in a LEO orbit with the orbital characteristics of the International Space Station (ISS). One satellite in the formation is designated as the "mother ship," and all communication between the satellites and the terrestrial network takes place via the mother ship. The terrestrial network is comprised of 12 ground stations distributed around the Earth. These ground stations are connected in a star topology with the White Sands Ground Terminal, New Mexico, at the center. Communication between the formation and ground stations, and among the ground stations is at OC-3.

Using the client-server paradigm, the satellites in the formation are simulated to function as servers and there is a single client at White Sands. The performance of this network is analyzed by simulating FTP file transfers. As an alternative to FTP, which uses TCP at the transport layer, the SAFE protocol, which operates over UDP, was also simulated. A set of comparative performance characteristics for these two protocols, FTP over TCP and SAFE over UDP, is included.

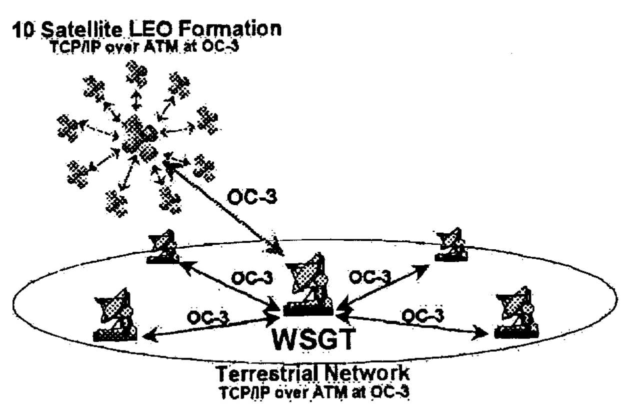

Figure 1-Network Configuration I

All spacecrafts within the formation are simulated to behave as servers, and files are transferred from each spacecraft in the formation through the mother ship to the terrestrial network. The spacecraft servers can use either FTP or the SAFE protocol in the application layer of the protocol suite. All terrestrial sites consist of routers that utilize an IP over ATM protocol architecture, and data received by a terrestrial site is forwarded to the White Sands Ground Terminal. The simulated White Sands Ground Terminal consists of a radio transceiver, which connects to a router, and all terrestrial sites in the network are connected to the WSGT router. The terrestrial client resides in the WSGT subnet and can use either FTP or the SAFE protocol in the application layer. The protocol architecture for Configuration I is shown in figure 2.

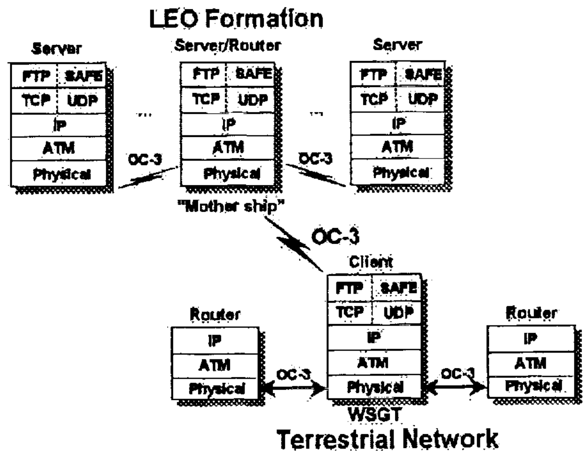

Figure 2-Configuration I Protocol Architecture

NETWORK CONFIGURATION II

The second simulation scenario differs from the first in that the IEEE 802.11 protocol architecture is used for communication, at 11 Mbps, between the satellites in the formation. The rationale for simulating IEEE 802.11 for a formation of satellites is that from a networking perspective, the formation can be viewed as a wireless LAN. Also, precise distances between satellites can be easily maintained. All other features of this configuration such as the number of satellites, mother ship, orbital characteristics, locations of ground stations and topology of the terrestrial network are identical to the first scenario. This enables us to evaluate the impact of using IEEE 802.11 for communication within the formation by comparing the same performance measures. Also, we compare the throughput of FTP/TCP with SAFE/UDP. Network Configuration II is illustrated in figure 3, and the protocol architecture is shown in figure 4.

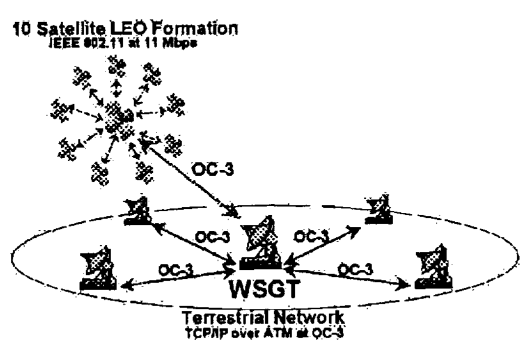

Figure 3-Network Configuration II

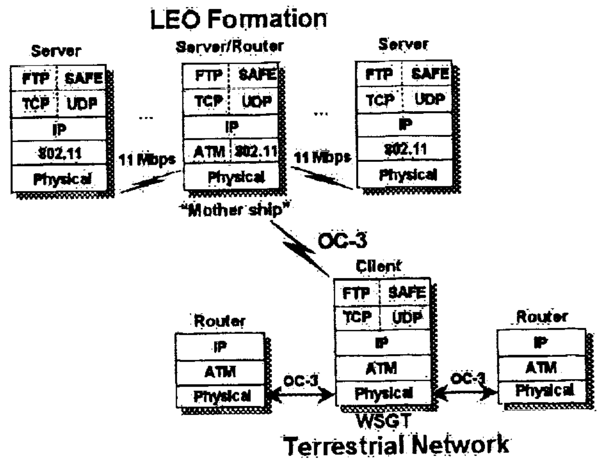

Figure 4-Configuration II Protocol Architecture

NETWORK CONFIGURATION III

The last configuration uses the topology and medium access techniques of the previous two network configurations. This time, however, a geosynchronous earth orbit (GEO) satellite constellation serves as an intermediate transfer point between the formation and the terrestrial sites. The advantage of this approach is that three GEOs can provide almost global coverage, and, therefore, the number of ground stations can be reduced. A disadvantage of this approach is the long propagation delay associated with using satellites in geosynchronous orbit. A comparison of the TCP/IP over ATM protocol architecture, as in the first network scenario, to the IEEE 802.11 protocol architecture, as in the second network scenario, is performed. Network Configuration III is illustrated in figure 5.

The orbital characteristics of the simulated geosynchronous satellites match those of TDRS-3, TDRS-4, and TDRS-5 and are located at 275° W longitude, 41° W longitude, and 174° W longitude, respectively. Due to the almost global coverage provided by the geosynchronous satellites, the number of ground stations is reduced to just two – the Guam Remote Ground Terminal (GRGT) and the White Sands Ground Terminal. The protocol architecture for the simulated satellites, however, differs from that of the TDRSS satellites. The node architecture for Network Configuration III is shown in figure 6.

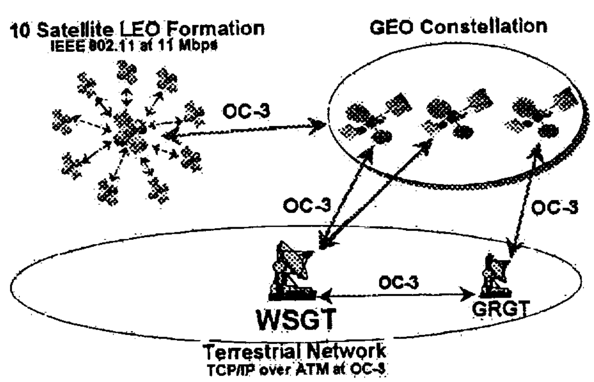

Figure 5-Network Configuration III

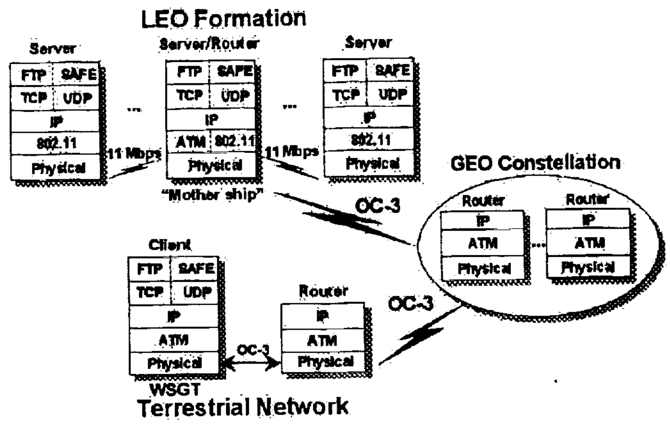

Figure 6-Configuration III Protocol Architecture

RESULTS

In order to compare the performance of Network Configuration I to Network Configuration II, the IP queuing delay and IP processing delay were observed at the central ship router; additionally, a comparison of application-level round-trip time is presented. Table 1 compares the IP queuing delay, IP processing delay and round-trip time for all three network configurations. Files of 100 kB were transferred at constant intervals of 300 sec for simulations of Configurations I and II,. For Configuration III, due to the complexity of the simulation scenario, smaller files of 10 kB were transferred at intervals of 300 sec. In all cases, using IEEE 802.11 for communication within the formation yields better results.

Table 1-Comparison of Network Configurations

	Configuration I	Configuration II	Configuration III/ATM	Configuration III/802.11
IP Queuing Delay	0.1211 ms	26.944 us	67.0138 us	21.1261 us
IP Processing Delay	0.1296 ms	30.150 us	69.6990 us	21.4038 us
Application RTT	2.6845 s	2.3243 s	2.3822 s	1.6779 s

The performance of the SAFE protocol was compared to FTP for all the configurations, using throughput as the performance metric. All simulations of FTP used TCP with a 64 kB receive window with the SACK option, window scaling option and the fast retransmit/fast recovery algorithms enabled.

Table 2-Average throughput (bps) comparison of SAFE and FTP for Configurations I and II

		SAFE	FTP
Configuration I	10 kB	34.05	32.2
	100 kB	199.35	179.07
	1 MB	3087.27	2399.66
Configuration II	10 kB	48.64	34.32
	100 kB	288.51	208.36
	1 MB	3211.12	2580.07

Table 3-Throughput comparison at WSGT for Configuration III

	Throughput from GEO-1 (bps)	Throughput from GEO-2 (bps)
SAFE/ATM	325.05	279.49
FTP/ATM	321.29	260.72
SAFE/802.11	289.81	234.29
FTP/802.11	286.23	227.26

CONCLUSIONS

All formation flying network configurations considered, which utilized the IEEE 802.11 protocol within the formation, yield lower queuing delay, processing delay, and application-level round-trip time. Since the 802.11 medium access technique allows stations to contend for access to a shared medium, the number of collisions is reduced, and hence delay is decreased and throughput is increased. Since the TCP/IP over ATM network configuration utilized a FDMA technique to gain access to the mother ship router, multiple stations can be communicating simultaneously. As a result, greater queuing delay and processing delay is required at the network layer of the mother ship router. This increase in delay results in lower throughput and increased round-trip time.

As shown in the preceding tables, SAFE exhibited higher throughput than FTP for all network configurations. Current research suggests that the contribution of the data-link layer protocol to the performance of application-layer protocols is not well understood and deserves further research. As the simulation results indicate, both the ATM protocol and the IEEE 802.11 protocol have an influence on the performance of SAFE and FTP. Despite this influence, SAFE still exhibits greater throughput than FTP, even though the difference is much less significant.

ACKNOWLEDGEMENT

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