CAPABILITY ASSESSMENT AND DESIGN EVALUATION FOR THE HYBRID NETWORK OF SPACE GIG AND TERRESTRIAL SENSOR NETS: GLOBAL MONITORING, TRACKING AND QUERY

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ABSTRACT

In this paper we propose a hierarchical architecture for organizing the hybrid network of the LEO-satellite based space network and terrestrial sensor nets. The hybrid network has unique advantages in providing global monitoring, tracking, and query capabilities. We assess these three capabilities of the network, and seek the optimal design in terms of the cooperation of the MAC and routing protocols. We evaluate six combinations of the MAC and routing protocols, and identify the best solution. Extensive simulation results are provided. Application models and performance metrics for the three capabilities are developed. The work provides a reference framework for pursuing global monitoring, tracking, query capabilities with hybrid space-terrestrial networks.

INTRODUCTION

Compared with terrestrial networks, LEO-based space network has great advantages in implementing global monitoring and tracking tasks. It has global coverage, runs in all-weather conditions, and is more secure and immune from physical and cyber attacks. This research envisions a network of LEO satellites as part of the global information grid (GiG) to provide global monitoring, tracking, and query services. The LEO-satellite based network is hence referred to as a *space GiG*. The space GiG cooperates with a number of terrestrial *sensor nets* distributed over the globe to realize the capabilities. So the overall setting is a hybrid network of satellites and sensors. In this paper we propose a hierarchical architecture to organize such a network so that capabilities of global monitoring, tracking, and query can be effectively supported. Two key components of designing the network are routing and MAC protocols. We provide several candidates for a design evaluation, and assess the capabilities under different designs. The results show potentials of the hierarchical architecture and give insights in protocol design for the important network. The work provides a basis for reaching a highly efficient design for future high-performance space infrastructure.

NETWORK ARCHITECTURE AND CAPABILITIES

The hybrid network is composed of the space GiG and ground sensor nets. The space GiG consists of a number of LEO-satellites moving on carefully designed orbits to achieve global coverage, as illustrated in figure 1. The ground sensor nets are a collection of separate networks that are deployed independently, which may reside in every corner of the earth to collect information of interest. These separate sensor net may be very different in terms of physical materials, sizes, topology, and low-level networking mechanisms. However, we assume each of them has a gateway node to communicate with the space network. These gateways run TCP/IP protocols and the communication is through IP over satellite. To the space network, the gateways are traffic sources. In general, sensor nets may generate various types of data, such as imaging, video, voice, and measurement data. So space GiG is a multi-serviced network with different QoS requirements. Figure 2 shows a 2-D view of the overall network involving sensor nets and satellites.

To support global monitoring, tracking, query capabilities, we propose to use a hierarchical architecture to organize the network. It involves additional devices – regional servers, which are indicated in figure 2, and its operation combines automatic and on-demand communication processes. The architecture is as follows. Divide the globe into n regions and put a server (possibly composed of multiple physical machines) in each region, i.e., the regional sever. The sensing data generated by all sensors in a region is transmitted and stored in corresponding regional server. Each regional server runs a spatial-database to manage the sensing data. Monitoring is an automatic process. When a random event happens in a sensor net, a report is sent through the space network to a regional server. The sensor net may also report periodically. Regional servers can be connected with high-speed terrestrial links, which allow them to fast send the data to a central server system for backup and global analysis. In the case that such connections are not available, the space path has to be used to relay the data. Then an on-demand data forwarding policy may be more feasible. That is, when a user needs data from multiple regions, he/she broadcasts a request to all regional servers, and each server only sends the requested data back to the user or the central server. Global tracking is a process that

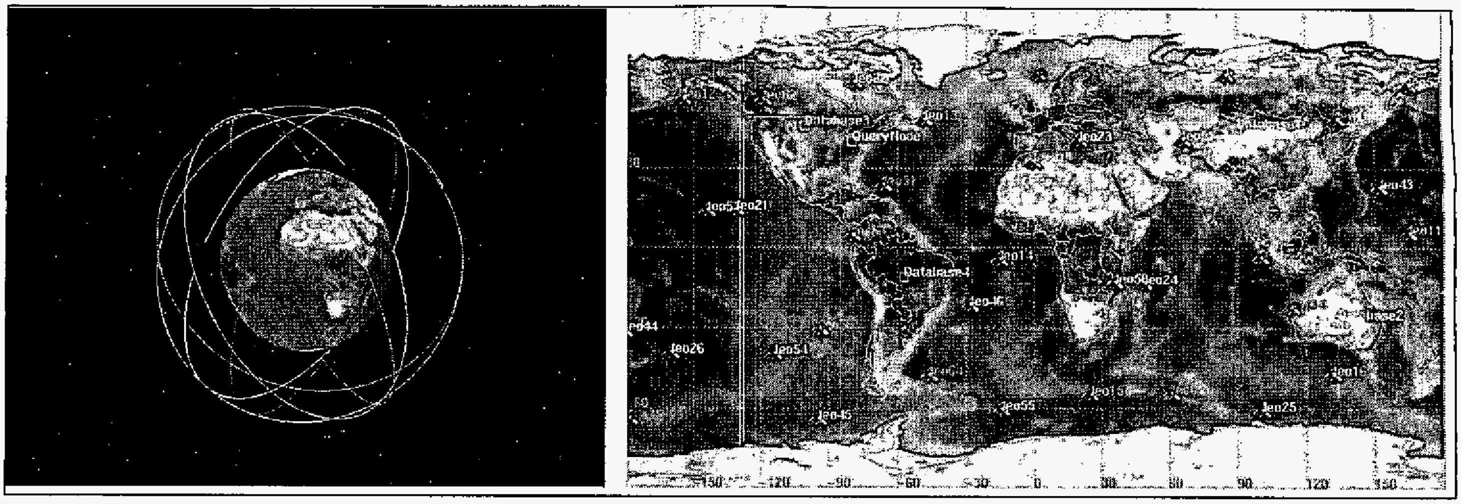

Figure 1. A Leo-based Space GiG. Left: 3-D view. Right: 2- D view. The objects in the right graph are Leo-satellites.

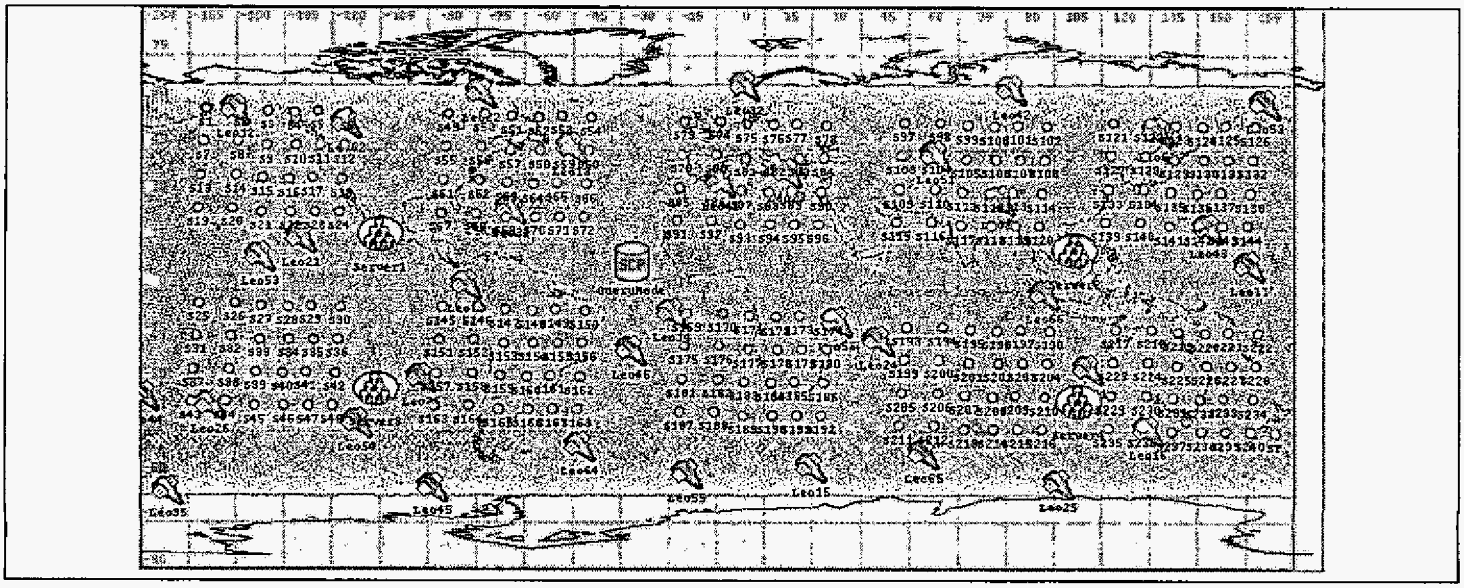

Figure 2. Hierarchical architecture of the hybrid network of space GiG and terrestrial sensor nets. The hammer-like objects are satellites. A green solid dot represents a sensor net. The eclipse balls are regional servers. The object labeled with "SCP" indicates the central database server and a representative query user.

needs coordination among multiple sensor nets. Space nodes equipped with sensors become space sensors, which often have advantages in tracking mobile objects. So the tracking process may also involve coordination among space sensors and between space sensors and terrestrial sensor nets. It may be started by network users in an on-demand manner or triggered automatically by events. Since tracking data are often required to be available to the user in real time, we consider a tracking operation flow that the sources directly send tracking data to the user or the central server bypassing regional servers. Data in regional and central severs can be queried by users from anywhere on the globe.

Global monitoring. The objective of this capability is to monitor events of interest in global scale and in real time. Targets may be static or mobile. The hierarchical architecture helps achieve real-timeness by using regional servers as local buffers. The data can then be forwarded efficiently by exploring high-speed terrestrial links or running on demand. Capability assessment is to answer questions like

a. How many sensor nets and events can the space GiG support given realtimeness requirement?

b. To support a certain number of sensor nets and events, how much bandwidth is needed for the space link?

Global tracking. The objective of this capability is to monitor and track *moving objects* in real time and in required accuracy. Key performance metrics are response time and spatial resolution of the target or accuracy of the information. We model two classes of moving targets. For one class the user only requires concise information such as location information. So a target triggers low-rate traffic flows. The other class features imaging, video, or audio information, which triggers high-rate traffic flows. The goal of capability assessment is to know how many moving targets the network can afford to be tracked simultaneously given response time and accuracy requirements.

Global query. The objective of this capability is for global users to query monitoring and tracking data from anywhere in the world. It is not much different from web server access if high-speed ground connectivity is available among regional servers. We will mainly assess the case when such connectivity is *not* available. A query is a request from a user for information like "What events happened during the period from t_1 to t_2 in the area X?" Based on the response, the user may further query related information, similar to web browsing experience. Capability assessment is to answer questions like "How many queries can be afforded at the same time if the response time must be less than d?"

ROUTING

To design a good routing algorithm for the hybrid network is a challenge. It is desirable to have an algorithm that routes messages among space nodes (satellites) and terrestrial nodes (gateways) seamlessly. The space nodes are constantly moving while the terrestrial nodes may be mobile or static. So the routing algorithm should be able to handle mobility efficiently.

Recently there is a big thrust of research on mobile ad hoc networks (MANET), which has produced many routing algorithms. A MANET is a highly dynamic network composed of mobile nodes that may move in any directions and at arbitrary speeds. A MANET routing algorithm tries to find paths for messages in spite of node mobility and changes of topology and link propagation property. So a MENET routing protocol is supposed to handle very complex mobility patterns and link conditions. In principle, it should has no problem to work in the space GiG and the hybrid network, because the mobility of space nodes is very predictable.

MANET routing protocols often use the on-demand approach to handle fast change of topology. That is, they only search for a path when it is required. This is usually done by broadcasting a path query message from the source node. The destination or any intermediate node that knows a path to the destination replies the query and a path can be established. The advantage of the on-demand approach is to avoid the overhead of searching for and maintaining paths that are never used by data messages. Meanwhile, the path established is based on fresh network status and has a good opportunity to be alive for a while for the message to get through. By contrast, a path based on not-so-up-to-date information is more likely to fail in a fast changing environment. We select two on-demand MANET routing protocols, DSR and TORA, and evaluate their feasibility for the hybrid network. Although both use the on-demand approach, they have significant differences. DSR is a source routing algorithm, i.e., information of a route is stored at the source node and is carried by every packet originated from that node. Intermediate nodes do not maintain routing tables. TORA is a special hop-by-hop routing algorithm, namely, every node decides the next hop. It uses a special metric associated with every link, height, to help make decision. The movement of a packet from the source to the destination is in analogue to water flowing downhill to a valley. At each hop, the packet can only choose a link whose height is lower than that of the previous hop. TORA support multiple paths. More details about the routing algorithms can be found in [1] [3] [4].

To have both the satellites and the terrestrial gateway nodes involved in the same routing cloud is a problem of cross-network routing protocol design. The key is to let routing messages get smoothly across the network boundary and move freely as the routing rule allows in both networks as if the boundary does not exist. Specific mechanisms are needed to manipulate the messages at the boundary. However, as long as the routing messages can not "sense" them, i.e., the mechanisms don't damage the routing messages or introduce logical conflict into the existing rule of the routing protocol, we are fine. In our implementation, we use some techniques to extend the MANET routing protocols to cover both the space and the terrestrial nodes. A particular concern is that we want the terrestrial gateways to be included, but don't want packets to explore paths on ground between gateway nodes. That is, the data path should be all within the space network except the source and the destination. In our current design, the uplink from ground nodes to satellite is a multi-access channel, and the downlink is a broadcast channel. The space network is the basic routing cloud. The techniques we use are as follows.

A. Uplink message handling.
Each gateway node maintains orbit information of satellites, with which it knows which satellite is nearest to it at any time. All outbound packets, including routing messages and data packets, will be forwarded *exclusively and directly* to the nearest satellite by the MAC layer. So routing messages generated by the gateway node enter the space network through the uplink. The uplink is thus active in the routing cloud. Since the routing messages are not aware of any link to other terrestrial gateway nodes, ground connectivity is disabled.

B. Downlink message handling.
At each satellite, routing messages are broadcasted to all neighboring nodes within the space network. In addition, they are forwarded to the downlink as well. If there are several ground nodes at the footprint of the satellite, the downlink broadcast channel is seen by routing logic as

multiple point-to-point links to each of those nodes. However, a data packet is routed differently. It is forwarded to the downlink only if the destination is at the footprint of that satellite. Therefore, the topology seen by data packets is different from that seen by routing messages. This guarantees that a data packet will not go down from space to ground to seek alternative path before it reaches the destination.

MAC SCHEMES

We can use separate beams for communications between satellites. The downlink broadcast channel can achieve very high bandwidth with current technology. Because of energy limit of sensor nets, the multi-access uplink is likely to be the bottleneck of the hybrid network. So the MAC protocol for the uplink has significant impact on the network performance. We evaluate three MAC protocols: Aloha, Aloha periodic stream (APS), and combined free demand assignment multiple access (CFDAMA).

Aloha is used as the baseline algorithm for comparison. APS is a reservation-based algorithm that has been commercially applied [5]. When a source node, i.e., a gateway node in our setting, has data to send, an Aloha request is sent to satellite. Upon receiving the request, a resource controller on the satellite assigns periodical time slots to it based on current active sources and their requests. If backlogged packets persist in the source node and exceed some threshold, additional bandwidth is requested by piggybacking requests in data packets. More bandwidth will be allocated until the maximum quota is reached or the backlog starts to decrease. A timeout value is set for the bandwidth allocation. If no packet arrives from the source node for the timeout period, the bandwidth allocated will be released.

CFDAMA [2] is a flexible reservation-based scheme. It first reserves bandwidth for source nodes based on demands. When there is no demand, the resource controller allocates free bandwidth to source nodes in a round-robin manner. So when traffic load on the link is not very high, multiplexing gain is explored. When the link is heavily loaded, the scheme behaves like a reservation scheme.

The two reservation-based schemes are designed to achieve high performance for satellite communication. So we choose them as candidates for evaluation.

EVALUALATION

Our objective is to evaluate different combinations of routing and MAC schemes, and assess capabilities under different combinations. Our target capabilities are global monitoring, tracking, and query, as introduced in Section 2. For each of the first two capabilities, we evaluate a full combination matrix of the two routing and three MAC algorithms, namely, six combinations. Since the traffic scenario of the query function is in many ways comparable to that of the monitoring, we select a best combination from the first two evaluations and asses the query capability under that "best" design.

The evaluation and assessment is based on the simulator OPNET v10.0. It includes DSR and TORA routing protocols. We add the techniques described in Section 3 and extend them to the hybrid network. We implement three MAC protocols, Aloha, APS, and CFDAMA in the simulator. We create the hierarchical network architecture and specific settings for assessment through configuration. The orbits of satellites and trajectories of moving targets are generated with specific tools. We also develop a simple database to store sensing data in servers, and a simple query protocol to retrieve sensing data. The database shares the same data format with reports from sensor nets. The data fields are defined as follows: <*NodeName*, *NodeId*, *Latitude*, *Longitude*, *Altitude*, *EventTime*, *EventType*, *EventData*>. A query message includes the following specification: <*Time1*, *Time2*, *Latitude1*, *Latitude2*, *Longitude1*, *Longitude2*, *EventType*>, which requests the data for events of type *EventType* that occur between *Time1* and *Time2* in the area between *Latitude1* and *Latitude2* and between *Longitude1* and *Longitude2*.

Network Setting

The network setting is largely the same as illustrated in figure 1 and figure 2. The space GiG consists of 36 LEO satellites moving on 6 orbits and each orbit has 6 satellites. The attitude of the satellites is 5,000 km. Each satellite is connected with four neighboring satellites with point-to-point wireless links. Each link uses a separate beam and has a bandwidth of 10 Mbps. There are around 100 sensor nets uniformly deployed on earth, each having a gateway node. The bandwidth of the uplink between a gateway node and the satellite nearest to it is 500kps, and the downlink bandwidth of a satellite is 1Mbps. There are totally four regional servers, each responsible for 1/4 of the earth surface. For example, server one stores data for the region from -180.0 to 0.0 Longitude and from 0.0 to 90.0 Latitude. Users can be anywhere in the world. In following evaluations of global tracking and query, the user is located at a nearly central position among the four regional servers, as indicated by the SCP node in figure 2.

Global Monitoring

In this evaluation, every sensor net sends reports to its regional server when events happen. All sensor nets run independently. So global sensing traffic converge to four points where the regional severs are located. Assume reports are generated by each sensor net randomly and data packets leave for the server at interval τ, where τ is an exponential random variable with mean T. The performance metric of interest is data packet delay from the source to the server. A realtime monitoring application may require the delay to be less than a threshold. Packet delay depends on the traffic load of the network, which again depends on the event frequency of each sensor net and the number of sensor nets. We fix the number of sensor nets for our network setting, and evaluate the packet

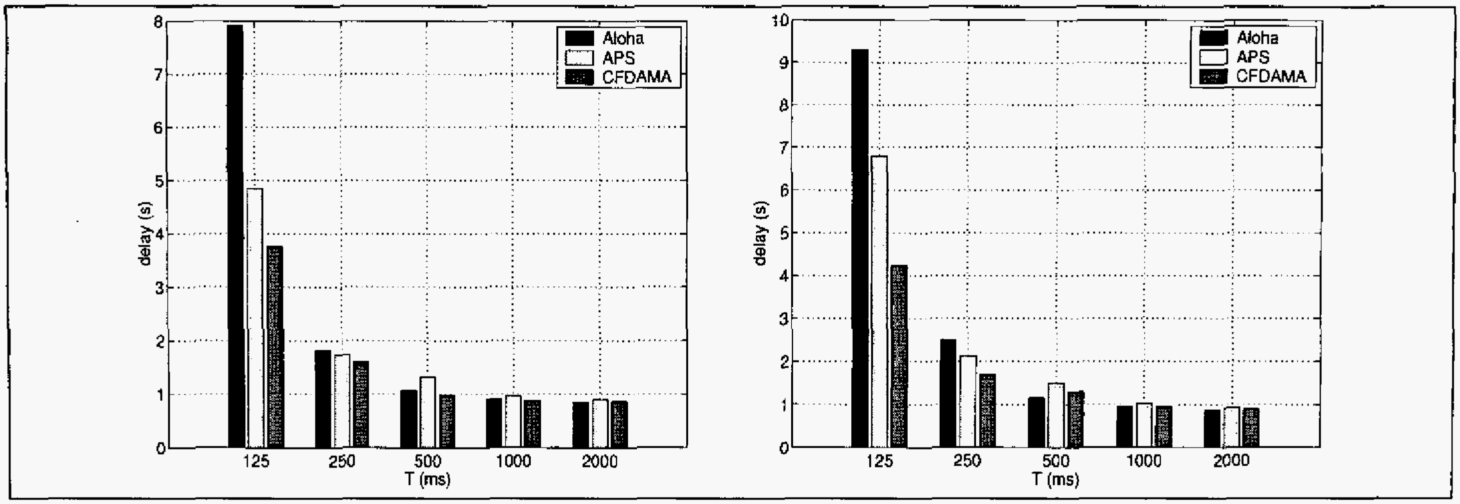

Figure 3. Performance of global monitoring with different routing and MAC protocols. Left: DSR. Right: TORA.

delay vs. the event frequency. How many events the network can afford indicates the monitoring capability.

We change *T* to change the event frequency, and compare the packet delay for different routing-MAC combinations. The packet size is 1KB. Figure 3 shows the result. With the increase of frequency or the decrease of *T*, the performance decreases significantly. When *T* changes by 16 times from 2000ms to 125ms, the performance of Aloha with either routing protocol changes sub-linearly by more than 8 times, and the performance of other two MAC protocols change by less than 8 times. Overall, the network runs at normal domain for all cases. However, the performance difference of different routing and MAC protocols are still very clear. In general, DSR performs better than TORA. The packet delay with DSR is shorter than that with TORA for every T no matter which MAC protocol is used. With regard to MAC protocols, CFDAMA is the best under both routing protocols in the sense that its performance decreases most slowly with the increase of traffic load. However, the simulations consistently show that at very light traffic, i.e., when *T* is large, Aloha outperforms other two MAC protocols.

Global Tracking

In this evaluation, moving targets are tracked while global monitoring is still going on and generating background traffic. We create three high-rate targets and two low-rate targets. Their serial numbers are 1, 3, 5 and 2, 4, respectively. Assume these targets are tracked by sensors on space nodes, i.e., when a target moves, the nearest satellite to it will generate tracking information. When a target moves out of the footprint of a satellite, the tracking will be handed over to another satellite along the target's moving trajectory. So during a tracking process, a series of satellites generate tracking information of the target in turn. We model the tracking information as periodical data blocks. The block size and inter-block interval for a high-rate target are 45KB and 250ms, respectively, and 5KB and 250ms for low-rate targets, respectively, for a low data rate target. We simulate different number of targets and observe tracking performance change with the increase of the number of targets. Targets are added in the order of serial number, one more in the next simulation. Global monitoring traffic is generated as described in Section 5.2 at background, and T is set as 500ms. The performance metric is tracking response time, which is the time delay to transfer a data block, which may include multiple packets, from the tracking sensor to the user.

Table 1. Initial and ending positions and velocities of moving targets

Target No.	Initial Latitude	Initial Longitude	Velocity (km/s)	Ending Latitude	Ending Longitude
1	65	-100	7.96	20	20
2	0	-135	7.60	20	20
3	-25	-135	7.69	20	20
4	55	120	7.61	20	20
5	-25	-135	7.69	20	20

The five moving targets and their trajectories are shown in figure 4. Their initial positions, velocities, and ending positions are listed in table 1.

Figure 5 shows the results with different routing and MAC protocols. When the number of targets increases from one to five, the response time is nearly doubled for all schemes. We see again that TORA has lower performance than DSR no matter which MAC protocol is used. CFDAMA protocol performs the best with either routing protocol. APS is only slightly better than Aloha when used with DSR, and is even worse when the number of targets is less than 4.

5.4. Global Query

In this evaluation, a query user continuously sends query requests to a server at a random interval *t*, where *t* is an exponential random variable with mean *θ*. It mimics the scenario that many users send many requests that share the same path, which is a "hard" case in which network performance likely degrades very fast. Just as in the case of global tracking, global monitoring is running in background when queries are

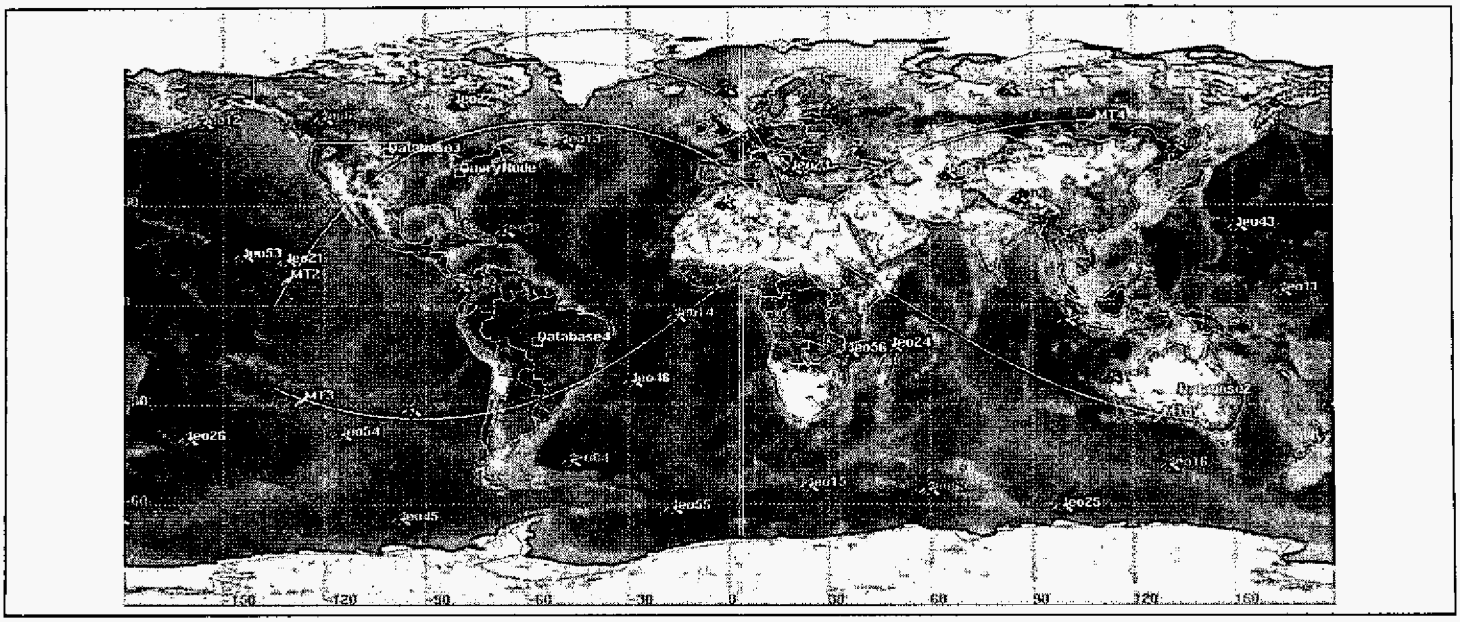

Figure 4. Moving targets and trajectories for tracking.

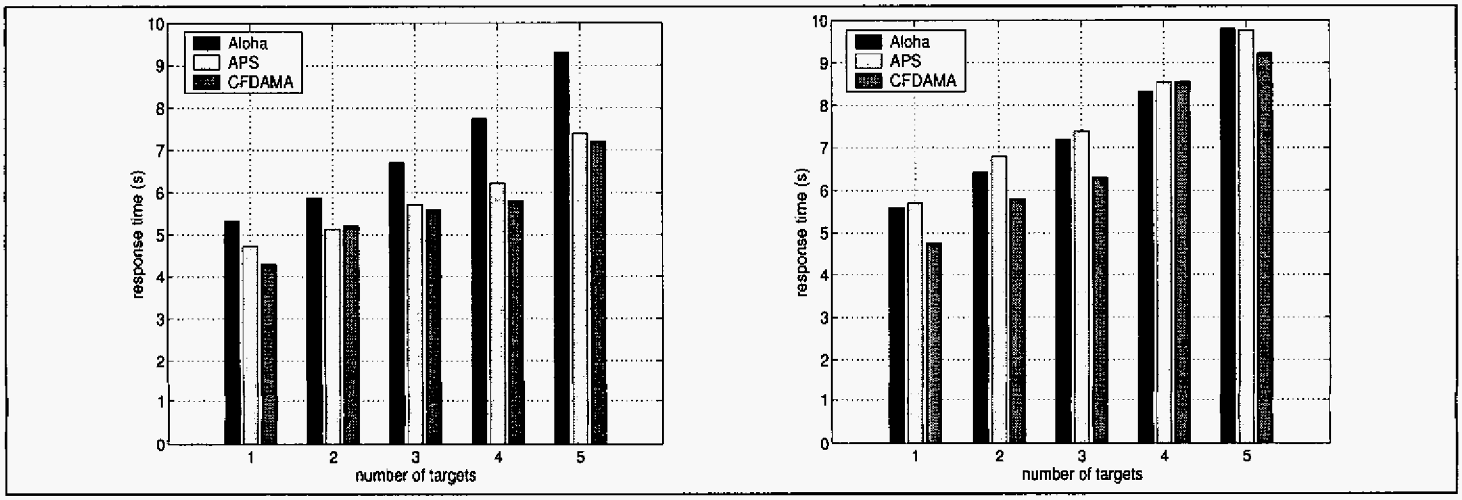

Figure 5. Performance of global tracking with different routing and MAC protocols. Left: DSR. Right: TORA.

carried out. T is set as 500ms. Each query request retrieves all data newly stored in the database in last 500ms, and sends it back to the user. We change θ to change the query frequency, and test the network's capability is supporting user access. The performance metric is query response time, which is the delay from the time when a user sends out a query to the time when the user receives the data. The average query response is usually required by applications to be less than a threshold. We use the "best" design suggested by previous two evaluations, i.e, the DSR+CFDAMA scheme, and evaluate performance change when the query frequency increases.

Figure 6 shows the average response time for different values of θ. When θ decreases from 2000ms to 125ms, i.e., the query frequency increases by 16 times, the response time increases by more than 2 times. The delay increase curve is quite flat. There is a good potential to increase the query freq-

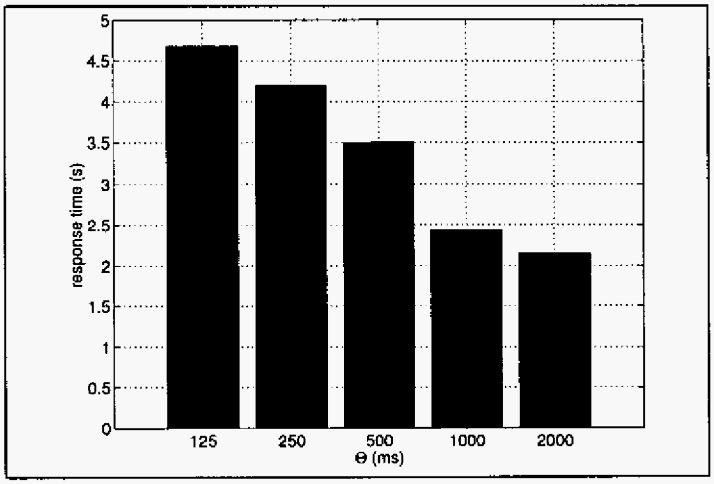

Figure 6. Performance of global query with routing protocol DSR and MAC protocol CFDAMA.

uency. So the DSR+CFDAMA scheme is also a good design for global query.

CONCLUSIONS

In this paper we investigate the architecture and design issues for hybrid network of space GiG and terrestrial sensor nets, and assess capabilities of the network under different design options. We target on three capabilities, global monitoring, tracking, and query, for which we believe the hybrid network has great advantages. A hierarchical architecture is proposed to organize the network to support the capabilities effectively. Routing and MAC protocols are important components that affect function and capabilities of the network. We make a proposal to design the routing protocol based on recently developed MANET routing protocols. Specific techniques are addressed to extend the routing protocols to hybrid network.. Three MAC protocols are considered as candidates for the uplink control of the network. A simulation-based prototype is developed that include all important components of the network. Various combinations of the routing and the MAC protocols are evaluated with the prototype for targeted capabilities. It shows that the combination of the DSR routing protocol and the CFDAMA MAC protocol is almost always the best option. The evaluations also show that the network architecture work well for all options, and it has very good potentials in supporting global monitoring, tracking, and query functions.

MANEAT routing protocols are generally more powerful than required by the space GiG and the hybrid network. We can take advantage of the predictable mobility of the latter to design more efficient routing protocols for them. We are also interested in building a more practical prototype system that involves real sensor nets, satellite links and commercial spatial databases to advance the technical development for such a hybrid global infrastructure.

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