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A Protocol for Satellite Access via Use of Spot-Beams

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ABSTRACT

In this paper, we develop a new protocol for multiple access to a GEO-satellite that utilizes an electronically-switched spot-beam. The emphasis is on an integrated voice/data protocol which takes advantage of the propagation latency, and which offers centralized control with excellent delay and throughput characteristics. The protocol also allows full exploitation of the advantages of a hopping beam satellite, such as smaller earth stations and frequency re-use.

INTRODUCTION

A protocol introduced in the early '80's, called Interleaved-Frame Flush-Out (IFFO) [1,2], provided for a reservations-based multiple-access to a geostationary satellite by means of time-division. The protocol had the properties of totally distributed control and of advantageous use of the propagation latency.

Recently, this protocol was modified to include voice and data service by means of the movable boundary idea, implemented in the time-domain, and of the isochronous slot assignment to voice calls [3].

In this paper, we consider the use of a hopping beam, and we show how the propagation latency and the periodic focus of each beam on subsets of users can be used to advantage in a similar way to that used in the structure of the IFFO protocols.

The main idea is to have a switch on board the satellite, such that the advantages offered by the hopping beam satellites, such as smaller earth stations and frequency re-use, can be fully exploited, while preserving the excellent delay and throughput characteristics of the original protocols, which use distributed control.

In the remainder of this paper, we first briefly describe the main features and characteristics of the IFFO protocol family, and we then proceed with the description of the model of our communication network with a single hopping beam satellite. Next, we present the new Hopping-Beam (Non-)Interleaved-Frame Fixed-Length (HB-IFFL & HB-NIFFL) protocols, and we outline a delay and throughput analysis. We further introduce an extension to Voice/Data applications, and we demonstrate the features of the new protocols with an example. We conclude this paper with a summary and an outlook to future research activities.

THE IFFL/NIFFL PROTOCOL FAMILY

The family of Interleaved-Frame Flush-Out (IFFO) protocols was introduced by Wieselthier and Ephremides in the early '80's [1,2]. They were mainly designed for totally distributed access control, taking advantage of the propagation latency, which is especially important for satellite links. The IFFO protocols are characterized by a frame length that adapts to bursty channel traffic, resulting in very high efficiency. In the Interleaved-Frame Fixed-Length (IFFL) and Non-Interleaved-Frame Fixed-Length (NIFFL), the frame length is kept constant, which is desirable for voice traffic. An overview of these protocols is given in [3]; in this paper, we concentrate on the fixed-length schemes applied to transparent satellites (bent-pipe).

We now briefly describe some characteristics which will be needed in the subsequent paragraphs: The IFFL/NIFFL protocols are characterized by fully distributed control and a frame length which is equal to the round-trip delay R, where R is measured in terms of slot durations. The frame consists of a status slot (denoted USS in Fig. 2) and $R-1$ traffic slots. The status slot is divided into M TDMA minislots, one for each earth station.

The reservation mechanism for the IFFL protocols works as follows: Each earth station transmits a reservation request in its minislot of frame k, based on the number of packets that arrived during frame $k-1$. After the roundtrip delay R, i.e., at the beginning of frame $k+1$, each earth station receives the requests of all other stations, and the traffic slots are then allocated in a fully distributed manner, based on all reservation requests and an algorithm known to all users. Hence, the messages arrived at an earth station during frame $k-1$ can be transmitted in frame $k+1$. If there are more reservation requests than traffic slots, the so-called excess packets are delayed until frame $k+3$, at which point they are again subject to further delays if there is again a large backlog. It can be seen that there are two interleaved packet streams, the even-numbered frames being independent of the odd numbered frames.

A variant of the IFFL protocols, called Fixed-Contention IFFL (F-IFFL) allows the transmission of packets during unreserved slots in a Slotted-ALOHA fashion, which considerably increases throughput with respect to the Pure Reservation IFFL (PR-IFFL) described above.

The NIFFL protocols are similar to the IFFL protocols, with the difference that if any unreserved slots are present in frame $k+2$, some or all of the excess packets of frame $k+1$ can be transmitted, without postponing them to frame $k+3$. In [3], the Voice/Data NIFFL (VD-NIFFL) protocols were introduced, using a reservation scheme for voice traffic and NIFFL for data.

SATELLITES WITH A SINGLE HOPPING BEAM

In our work, we focus on satellites with hopping beams. Such satellites offer many advantages, such as a higher received power on the ground due to the focusing beam antenna of the satellite, i.e., the transmitted power is no longer spread over the whole hemisphere, but concentrated on a circle with, say 150 miles in diameter. This allows frequency re-use, and, hence, many parallel communications channels.

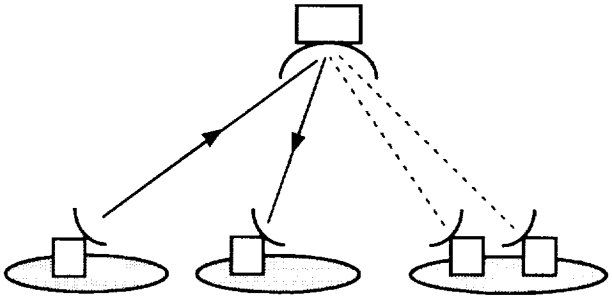

Figure 1: Network Configuration: There are a total of M earth stations in B footprints.

In this paper, we consider a communications network that consists of a satellite with a single hopping beam and M earth stations in B footprints (see Fig. 1), M_b stations in beam b:

$$M = \sum_{b=1}^{B} M_b. \tag{1}$$

We assume that the switching time of the beam is small compared to the burst length (e.g. for the NASA ACTS satellite, the switching time is < 75 ns). We further assume that there is enough memory on-board the satellite to buffer traffic for one slot, that signal processing on board the satellite is very fast, and that the satellite knows which earth station is in which beam.

THE HB-IFFL PROTOCOL FAMILY

In this section, we will show how the IFFL/NIFFL protocols can be modified for use with a satellite with a single hopping beam. The main idea is to use a switch on board the satellite in a way that the access control is now centralized, although it seems to be distributed from the user's point of view.

The Hopping-Beam Interleaved-Frame Fixed-Length (HB-IFFL) protocols are, like the IFFL/NIFFL protocols, reservation-based time division multiple access (TDMA) control, where non-reserved contention slots may be accessed by each user. However, while for the IFFL/NIFFL schemes it was assumed that all earth stations can receive all the traffic transmitted by the satellite, this no longer holds for the hopping beam satellite. We therefore have to find a way to transmit the outcome of the reservation process to all earth stations. This will be done by having a switch on board the satellite, which allocates reserved traffic slots to the earth stations, as will be explained in the sequel.

The uplink frame structure of the HB-IFFL protocols is depicted in Fig. 2. Each frame consists of an uplink status slot (USS) and $L_k - 1$ data slots, where L_k is the frame length. The uplink status slot is divided into M TDMA uplink slots, one slot for each station. The downlink frame structure is similar, with the difference that the downlink status slot (DSS) is divided into B downlink slots, one for each footprint.

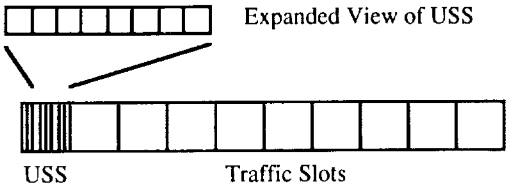

Figure 2: Uplink Frame Structure: There are $L_k - 1$ traffic slots and one Uplink Status Slot (USS), which is divided into M TDMA minislots.

The reservation mechanism works as follows (see Fig. 3): The satellite switches its uplink beam such that each of the M stations is covered during its minislot. In its minislot in frame k, each station transmits information about the packets that arrived in frame $k - 1$, i.e., the number of slots it wants to reserve for each receiving station in frame $k + 1$ (e.g. one packet for station 7 and three packets for station 9)[1].

The satellite receives the USS of frame k with a delay of R/2 slots and decodes it immediately. It then composes the beam/switching pattern for frame $k + 1$ and transmits it sequentially on all B beams. Hence, each minislot of the DSS contains the same information, namely the beam pattern, dwelling time and transmitting time for each station in frame $k + 1$.

Because the satellite has to receive the entire USS before it can compose and transmit the DSS, the DSS is transmitted $R/2+1$ slots after the USS. The DSS then arrives at the earth stations after another $R/2$ slots, or $R + 1$ slots after the transmission of the USS. Hence, it is natural to select the frame length L_k to be greater than or equal $R + 1$ (instead of R, as for the IFFO protocols).

The R traffic slots of each frame are simply delayed by one slot at the satellite before they are transmitted on the downlink[2].

Upon reception of the DSS by the earth stations, each earth station knows if its reservation request has been granted, and it can start to transmit immediately in the traffic slots that were reserved for it.

Hence, with the "trick" of the on-board switch, the HB-IFFL protocols behave very much the same way as the original IFFL protocols, with a slightly increased frame length, however.

DELAY AND THROUGHPUT ANALYSIS

In this next section, we provide a brief throughput and delay analysis for some variants of HB-IFFL. We characterize these variants, we try to relate the analysis to that of the IFFL/NIFFL protocols where this is possible, and we point out the differences.

We assume that each of the M earth station has a buffer in which to store arriving packets, which are assumed to form a Bernoulli process with rate λ in every slot. The total arrival rate is, therefore, $M\lambda$ packets per slot, which is equal to the throughput rate under stable operation, since no packets are rejected.

PR-HB-IFFL

This Pure Reservation scheme is the one we described in the previous section. It is characterized by the fact that unreserved slots are not used for contention. An analysis similar to PR-IFFL, which is based on a Markov Chain representation, can be used [3], with frame length $R + 1$ instead of R, and delay $R + 1$ instead of R.

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[1] This procedure is similar to IFFL/NIFFL, but here not only the number of packets, but also the destination address has to be transmitted

[2] An alternative would be to insert an empty slot *after* the USS. Then the satellite could simply repeat each incoming uplink slot on the downlink. The idle slot would then appear on the downlink at the end of the frame, i.e., *before* the DSS. However, this results in a reduced throughput.

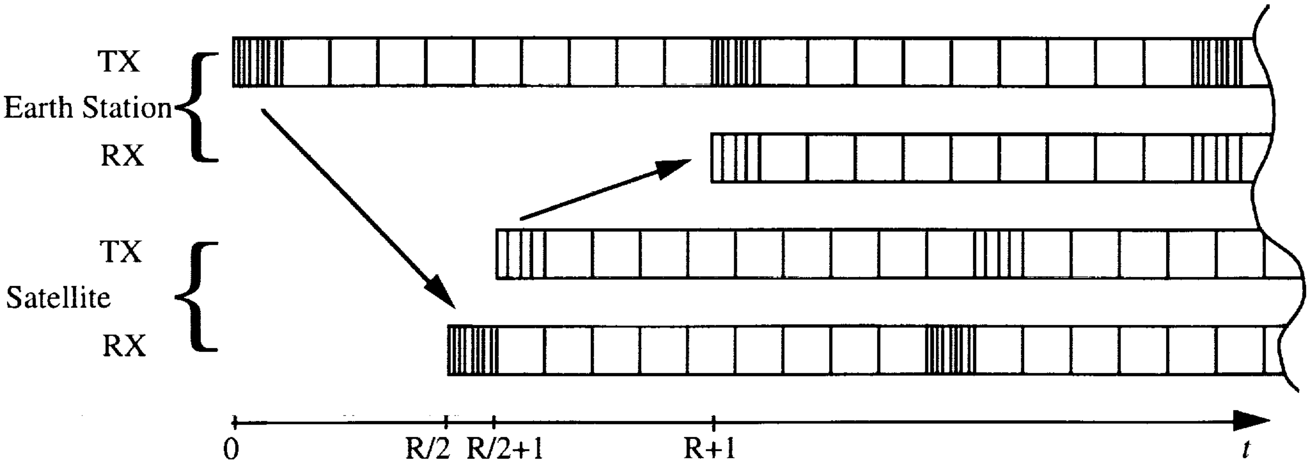


Figure 3: Sequence of Up- and Downlink Status Slots: At time 0, the USS of frame k is transmitted by the earth stations to the satellite, where it is received at $R/2$. The satellite transmits the DSS at $R/2+1$, and the earth stations receive it at $R+1$.

F-HB-IFFL

This scheme is similar to PR-HB-IFFL, but unreserved slots can be used for contention in a predefined way, using some Slotted ALOHA mechanism. Note that due to the hopping beam, the F-IFFO analysis cannot be applied. We have to consider two possibilities of packet loss:

- Packets of the stations in the same footprint collide. The probability of this happening is smaller than for F-IFFL when there is more than one footprint.
- Packets are lost because the hopping antenna of the satellite is not listening to the right footprints at the right time.

Hence, it can be seen that to quantify the second item of the above list, we have to define the hopping pattern of the satellite during non-reserved slots, and the way each earth station transmits packets during these slots. We consider two different strategies:

1. During the unreserved slots, the satellite's beam hops in a manner unknown to the ground stations. The ground stations transmit their packets according to some algorithm (maybe more than once during a frame). A packet is only received by the satellite if it is transmitted while the satellite is listening, and if there is no collision. The DSS will contain information about successfully received packets, such that all earth stations are informed about success of failure of their transmissions.
2. The satellite announces in the DSS what hopping pattern it will use during the unreserved slots (according to some algorithm, which may use information about excess packets). The ground stations transmit their packets according to some algorithm (e.g. with a given probability) while the satellite is listening. As mentioned before, the DSS will contain information about successfully received slots.

For a large number of beams, strategy (1) has a low probability of success because of the low probability that the satellite is listening to the right footprint. Hence, strategy (2), seems to be more promising. The algorithm for earth stations to transmit their packets has to be designed carefully, however, in order to reduce the probability of collisions. The exact analysis of delay and throughput is yet to be elaborated, but it can be said already that the advantage of F-HB-IFFL over PR-HB-IFFL will probably be smaller than of the corresponding IFFL schemes.

PR-HB-NIFFL

These Pure-Reservation Hopping-Beam Non-Interleaved-Frame Fixed-Length protocols are similar to PR-HB-IFFL, with the difference that if any unreserved slots are present in frame $k+2$, some or all of the excess packets of frame $k+1$ can be transmitted, without postponing them to frame $k+3$. Hence, the even- and odd-numbered frames are no longer interleaved. Because the satellite knows about the excess packets (it received the requests for the previous frames), it can adjust its hopping pattern an transmit this information on the DSS. Hence, the same delay and throughput analysis as for PR-NIFFL can be used, which is based on a first-order Markov chain [3], with the modification of the frame length and delay ($R+1$ instead of R).

F-HB-NIFFL

This scheme is similar to PR-HB-NIFFL, but unreserved slots can be used for contention in a pre-defined way, using some Slotted ALOHA mechanism. As already mentioned for the interleaved version of this protocol, the F-IFFO analysis cannot be applied because of the hopping beam. The same comments as above apply, i.e., the delay and throughput analysis strongly depend on the contention algorithm used by the earth stations.

VOICE/DATA APPLICATIONS

The new protocols described in this paper can be extended to Voice/Data application much in the same way as originally suggested in [3]. These Voice/Data HB-NIFFL (VD-HB-NIFFL) protocols use a reservation scheme for voice traffic and HB-NIFFL for data. Once a voice call is accepted by the system, it is guaranteed access to one slot in each frame until completion. Each frame is divided into voice and data slots, where it is appropriate to define the maximum number of voice slots V_{max} such that $V_{max} \leq R$. Voice calls are accepted as long as the total number of calls does not exceed V_{max}, otherwise they are blocked. In the so-called fixed boundary implementation, data packets are transmitted in the data slots using one of the NIFFL protocols, whereas in the movable boundary implementation, data packets may also be transmitted during unused voice slots.

Performance parameters of the VD-HB-NIFFL protocols are the blocking probability of voice calls P_b and the packet delay for data. Assuming that voice calls arrive with poisson rate λ_V and that the call duration is exponentially distributed with parameter μ_V, the well-known Erlang formula can be used to compute P_b. For the data packets, the delay analysis for the movable boundary scheme is more complicated, because the number of packets which can be transmitted in a frame depends on the number of on-going voice calls. For a detailed analysis, the reader is referred to [3].

EXAMPLE

In this section, we quote an example from [3] to quantify the performance of the VD-HB-NIFFL protocols. Since we want to minimize both the call blocking probability P_b and the expected packet delay $E(D)$, we use a weighted sum as our performance measure:

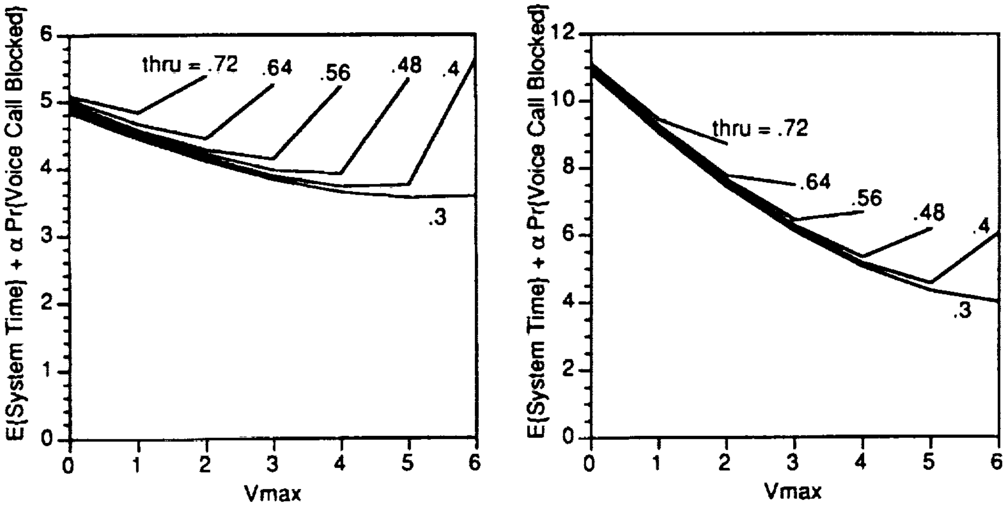
$$E(D) + \alpha P_b, \qquad (2)$$

where α is the weighting factor. We assume that there are a total number of $M = 10$ users and that the roundtrip delay is $R = 11$ slots (which for a geostationary satellite and a data rate of 64 kbps corresponds to a voice data rate of about 5.8 kbps).

Fig. 4, which is taken from [3], shows the weighted performance index as a function of V_{max} for the fixed-boundary version and two values of α, i.e., 2 and 8, where delay is normalized with respect to the frame length $R+1$. In each case, curves are plotted for a fixed value of data-packet throughput. Note that for throughput values of 0.48 and greater, the curves terminate at values of $V_{max} < 6$; in each of these cases the value of the throughput corresponds to a utilization of 0.96 for the corresponding value of V_{max}. Throughput values that correspond (for a specific value of V_{max}) to a utilization of 1.0 or greater result in infinite delay, and hence an infinite value of the weighted performance index.

SUMMARY AND OUTLOOK

It was shown that the IFFL/NIFFL protocols, which were designed for a transparent satellite [3],



(a) $\alpha = 2$

(b) $\alpha = 8$

Figure 4: Weighted performance index for fixed-boundary PR-VD-HB-NIFFL (roundtrip delay R=11 slots, M=10 users..

can easily be adapted for satellites with a single hopping beam and an on-board switch. The excellent delay and throughput characteristics of the original protocols could be preserved, while allowing for making full use of the advantages offered by the hopping beam satellites, i.e., smaller earth stations and frequency re-use. Note that due to the on-board switching, delays of these protocols using centralized control are similar to protocols using fully distributed control, as opposed to traditional centralized control access schemes which involve a double hop over the satellite link, and, hence, double the delay.

We conclude this paper by listing some questions to be addressed in future work:

- What is the optimum strategy for earth stations to transmit excess packets during unreserved slots?
- How does distributed flow control on the ground improve system performance?
- Does on-board memory increase throughput? What about on-board flow control?
- What is the trade-off between call blocking probability, delay and buffer overflow ? Jordan and Varaija [4] showed that the blocking of some calls even when resources are available may result in a decrease of the overall blocking probability. Can this result be applied to the HB-NIFFL protocols?
- How can these protocols be applied to satellites with multiple hopping beams?

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