Time Division Duplex for Satellite Communications

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Abstract—**Satellite communications increasingly make use of on-board processing along with phased array technology to allow improved capacity. Conventional satellite operation uses frequency division duplex, requiring heavy duplexing filters for each of the array elements. If this could be eliminated then satellites with more beams and/or lower cost should be possible. This paper proposes a method for allowing satellites to operate time division duplex in spite of the very large round trip propagation delays.**

satellite; time; division; duplex

I. INTRODUCTION

Satellite communications increasingly make use of on board processing along with phased array technology to allow improved capacity. Conventional satellite operation uses frequency division duplex (FDD), requiring heavy duplexing filters for each of the array elements. If this could be eliminated then satellites with more beams and/or lower cost should be possible.

The conventional alternative to FDD is time division duplex (TDD). This would eliminate the need for complex, heavy and costly diplexer filters required for FDD. Traditionally, the use of TDD has been associated with short to medium range terrestrial links where the propagation delays can be kept small in comparison with the length of the frames for TDD operation. This has been a requirement because conventional wisdom was that the TDD frames needed to incorporate guard periods equal to the maximum round trip propagation delay in order to avoid interference between uplink and downlink under worst-case conditions.

The above constraint would clearly be prohibitive in a satellite application given a minimum round trip delay of order 240 ms minimum. Thus it is necessary to re-think concepts for TDD in a satellite context to allow operation with high efficiency (minimal guard time) and low marginal delay (short TDD frame).

In the following, section II introduces the basic concept for allowing low marginal delay TDD in satellite context with higher efficiency. Section III introduces a simulation for evaluating the interference effects on the ground. In section IV a new algorithm for assigning uplink time slots is presented along with simulation results. Section V discusses the issue of inter-satellite interference whilst section VI briefly presents possible operation of control channels.

II. BASIC CONCEPT

In several applications such as DECT, the use of TDD has been combined with time division multiple access (TDMA). By applying these technologies together and making some additional changes it can be shown that the above requirements can, to a large degree, be met.

Consider a simple TDD scheme. The satellite round trip propagation delay being large, it is highly desirable that any physical layer related delays do not add to this significantly. For this reason the TDD frame length should be chosen to be a small fraction of the propagation delay. Suppose the one way propagation delay is exactly five times the frame length. The situation is illustrated in Figure 1.

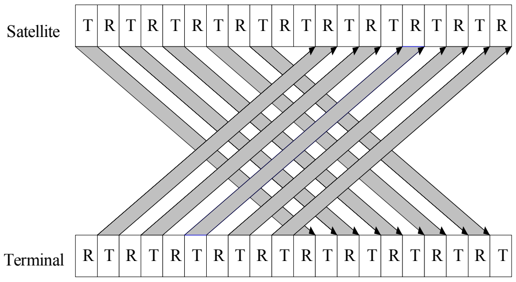

Figure 1 Basic TDD – Ideal Timing

In this case the situation is ideal as every satellite transmission coincides exactly with a terminal receive time slot and vice versa. However, now consider the case where the one-way propagation delay is 4.75 times the frame length. This is illustrated in Figure 2

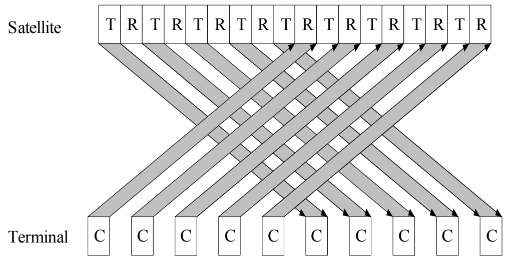

Figure 2 Basic TDD – Worst Case Timing

In this case the timing established by the satellite forces the terminals to receive and transmit at the same time (‘C’ denotes ‘conflict’). This is only possible if two separate frequencies are used which defeats much of the object. Half of the time is wasted altogether and the other time is unusable.

Considerably more flexibility applies when there is an additional TDMA element. At this stage we introduce the concept of *Reversed TDMA/TDD*. In conventional regular TDMA/TDD such as DECT, all of the downlink transmissions are grouped together in time and followed by the uplink transmissions. In reversed TDMA/TDD, every uplink time slot is followed by a downlink time slot. The TDD mode of UMTS has the flexibility to operate in this way but is not prescribed to do so. An example of this operation is shown in Fig. 3

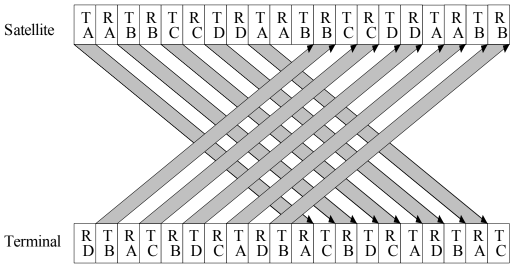

Figure 3 Reverse TDMA/TDD – Best Case Timing

In this example there are four TDMA time slots, A, B, C and D. As an example, a block TC denotes transmitting to/from terminal C; RD denotes receiving at/from terminal D. The links are transmitted and received sequentially from/at the satellite. Note that because of the propagation delay, the time slots for reception and transmission have a different relationship on the ground from in the satellite. Fig. 3 shows the relationships for best-case time. For worst-case timing we have the situation of Fig. 4

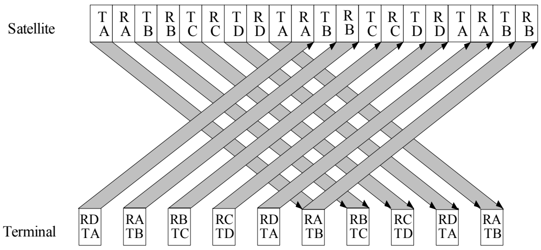

Figure 4 Reverse TDMA/TDD – Worst Case Timing

Here we see that, as before, transmission and reception is required on the earth at the same time. However, these requirements are not at the same place. Thus, for example, terminal D must receive while terminal A is transmitting. If the range between these terminals is large enough then the interference path will be negligible so this will be possible. Moreover, the order of the uplink time slots may be scrambled in such as way as to maximize the distance between mutually interfering terminals.

In practice the terminals will be spread over an area large enough such that the propagation delays to the satellite will vary considerably – i.e. by many time slots. Far from being a problem this effectively randomizes the interference and availability of uplink time slots that do not overlap with the corresponding downlink time slot.

The operation, then, is as follows. All timing is synchronous at the satellite but the timings on the ground depend on the propagation delays. Thus terminals are set to receive at the point when their time slot reaches their location. They transmit at the time necessary to ensure that their signal is received into the allocated uplink time slot at the satellite.

III. SIMULATION

A simulation was written to evaluate the performance of such a system. The operation of the simulation was as follows…

- A geostationary satellite was placed
- A coverage area with circular perimeter was identified directly underneath the satellite. Initially this area was the maximum that gave satellite visibility (satellite elevation 0° at perimeter)
- A fixed number of terminals was deployed randomly with uniform distribution over the ground
- The great circle distances between all terminal pairs were computed
- Downlink time slots were assigned arbitrarily to each terminal
- Uplink time slots were assigned initially in the same order as the downlink time slots but with provision for some slots to be shifted if they require a terminal to have overlapped receive and transmit times.

The distances between terminals were used to determine any cases where one terminal's transmission, delayed by the propagation time, overlapped with another terminal's reception time. For those cases, the distances between terminals were noted.

A simulation was run for 100 terminals, with a slot length of 100 µs. Surface plots give an indication of the effect – see Fig. 5.

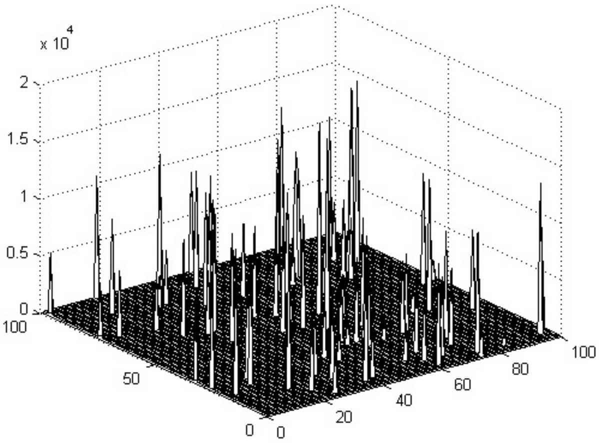

Figure 5 Non-Optimized Interference Relationships – Maximum Coverage

The X and Y co-ordinates identify a pair of terminals. If the Z value is zero at this position then there is no interference between the terminals. Otherwise the height indicates the distance between the interfering terminals. For the example shown the worst case (minimum) distance between interferers was 926 km. This is more than adequate for acceptable interference. However, we shall see that in the general case we will need to, and can, do better.

IV. UPLINK TIME SLOT ASSIGNMENT ALGORITHM

In the example shown, the uplink time slots were allocated without reference to ground-to-ground interference effects. A more sophisticated assignment allocation has been developed. This is based on the assumption that the satellite knows the positions of the terminals. This is reasonable if the terminals have GPS/Galileo receivers and can relay their position information to the satellite on some control channel. The positions are only needed to a coarse degree so even with relatively high mobility this information would only need to be transferred infrequently. The principles of the optimizing algorithm are as follows…

1. Assign the downlink slots. At this stage it is assumed that this can be done arbitrarily.
2. For a terminal examine the effects of assigning a time slot in terms of the potential for that terminal interfering with other terminals' downlinks. Compute the worst-case interference that results – i.e. the minimum distance between the transmitting terminal and the interfered terminal. Repeat for all possible time slots. Repeat for all terminals.
3. For every terminal, determine the worst-case interference that will result if that terminal must use its worst time slot.
4. Rank the terminals in order from the terminal that would have the worst interference if using its worst time slot, to the terminal that would have the least worst interference if using its worst time slot
5. Starting with the worst terminal, assign each terminal the best available time slot. In deciding on available time slots ignore any time slot resulting in the terminal having overlapped receive and transmit times.

This algorithm was applied to the above case (actual terminal positions). The interference relationships are shown in Fig. 6. As can be seen there are far fewer.

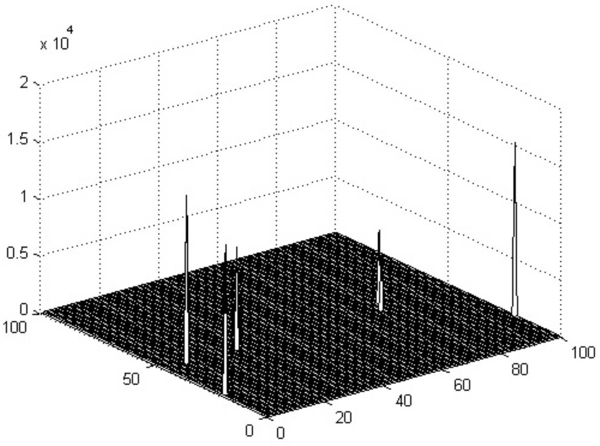

Figure 6 Optimized Interference Relationships – Maximum Coverage

The minimum range to an interferer is now 4,670 km. This represents an improvement by a factor of over 5:1.

Given the ranges available without optimization, this improvement may seem academic. However, as stated earlier, one of the purposes of using TDD is greater to facilitate the use of phased array antennas. This will allow spot beams. It will be desired to use all time slots within a spot beam coverage area and this area will be far smaller than the entire footprint of the geostationary satellite. For example, we might have a footprint of about 60 km radius. The results for a typical scenario are shown in Fig. 7.

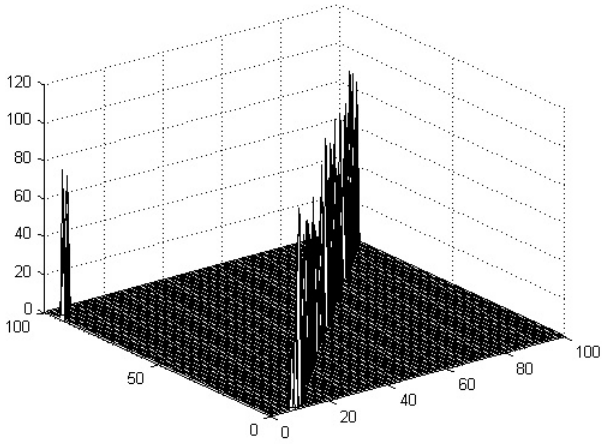

Figure 7 Non-Optimized Interference Relationships – 60 km Radius

The minimum distance between interferers is 6.5 km. Occasionally much lower distances can arise. After optimization according to the assignment algorithm, we see the scenario of Fig. 8.

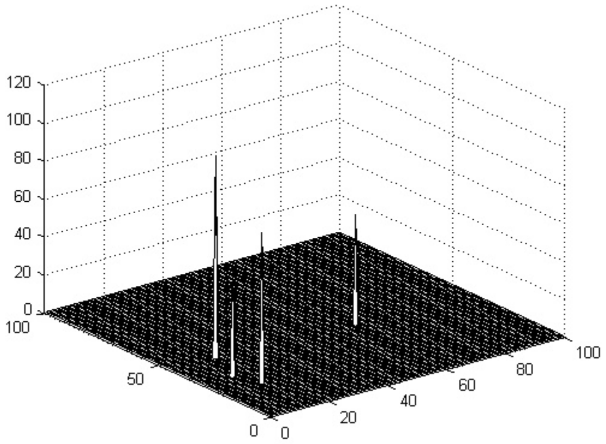

Figure 8 Optimized Interference Relationships – 60 km Radius

The minimum distance is now 57.5 km. We see that the minimum distance is a significant fraction of the diameter of the cell.

The above results are only examples. To obtain more statistically significant results the simulation was run 1,000 times with different random positions for the terminals. The cumulative distributions of minimum range in km for both with and without the optimization are plotted in Fig. 9

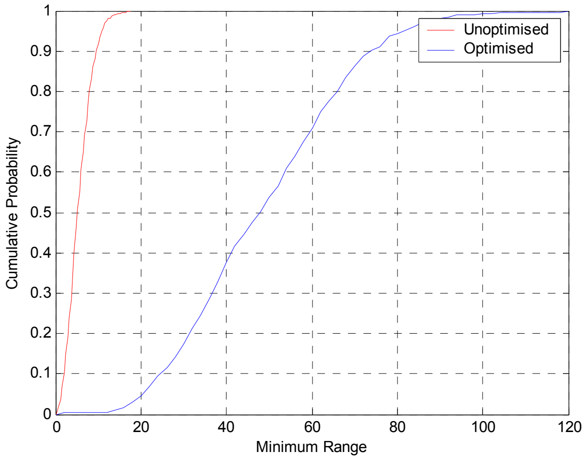

Figure 9 Cumulative Distribution of Minimum Distance (km)

We can see that the optimized case is significantly better than the un-optimized case. There are a small number of cases where the range may be unacceptable. Further improvement of the algorithm is expected to deal with these cases. Even without this, only a tiny proportion of time slots would be unusable due to interference.

In practice the minimum acceptable distance between mutually interfering terminals will depend on many factors, including the terminal antenna pattern, the operating frequency, the link path loss capabilities and the intervening terrain. Nevertheless, the kind of minimum distances achieved by the algorithm in these examples should be more than sufficient for any feasible situations.

V. INTER SATELLITE INTERFERENCE

One potential problem with TDD is that not only can terminals interfere with terminals but satellites with satellites. For the case of 3 geostationary satellites covering the earth this is not a problem because the mutual ranges are greater than the satellite to ground ranges. Specifically, simple geometric considerations show that the worst case (i.e. for terminals on the edge of the coverage region) range ratio is about 1.85:1 corresponding to 5.4 dB in free space. Given the additional effects due to antenna patterns, inter satellite interference will not be a problem

The above conclusion is satisfactory but unfortunate in that it appears to limit operation to cases where there are few satellites. In fact it is possible to bring the satellites closer together by ensuring that the propagation delays between adjacent satellites are whole multiples of the TDD period (i.e. twice the slot period – 200 µs in our example corresponding to multiples of about 6 km). If this is achieved then transmissions from one satellite will arrive completely overlapped with transmission slots for its neighboring satellite. For non-neighboring satellites this relationship will break with increasing neighbor distance because the geometry of a circle will gradually take over. Thus in Fig. 10, D ≠ 2d.

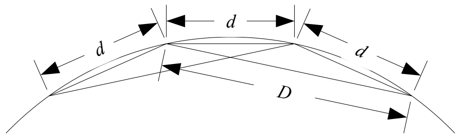

Figure 14 Satellite Distance Geometries

However, if satellites are deployed at relatively short mutual distances then their coverage areas will be reduced on the ground so that their antennas will point more directly downwards leading to greater discrimination between the satellite to ground directions and the satellite to satellite directions.

VI. SYSTEM ISSUES

It will clearly be necessary to set up calls. This will require a broadcast (BCH) and a random access channel (RACH).

We need an acceptably low probability that any a terminal in any location will be unable to hear the BCH. Self jamming of the BCH is caused by an active user, close enough to desensitize the terminal, transmitting in a time slot such that its reception at the victim terminal overlaps with its received timing of the BCH. This depends on the density of active users and the number of time slots and will generally be low. The probability can be further reduced subtantially by introducing a number of repeated BCH time slots spread uniformly over the TDMA frame.

Transmissions into the RACH channel should ideally be made without causing interference to reception at active terminals in the vicinity. However, given the relatively low duty cycle of RACH transmissions, some interference might be acceptable. If RACH time slots are replicated it may be possible for the user to use terminal position information broadcast on the BCH to determine which of the RACH time slots would cause least interference to its neighbours. However, the overhead in broadcasting all of this information might be unacceptable.

VII. CONCLUSIONS

A novel approach for allowing satellites to operate time division duplex has been presented. This approach overcomes the problems of large guard period leading to inefficiency and long propagation delays.

The problem of interference in a TDD systems with large propagation delays has been solved by intelligent assignment of uplink time slots to bring wide spatial separation between interfering terminals.

Nominal duplexing efficiency is 100% in the vast majority of cases with a minor overhead for signalling.

This capability can greatly enhance the scope for low cost multiple beam satellites with on-board processing.

ACKNOWLEDGMENT

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