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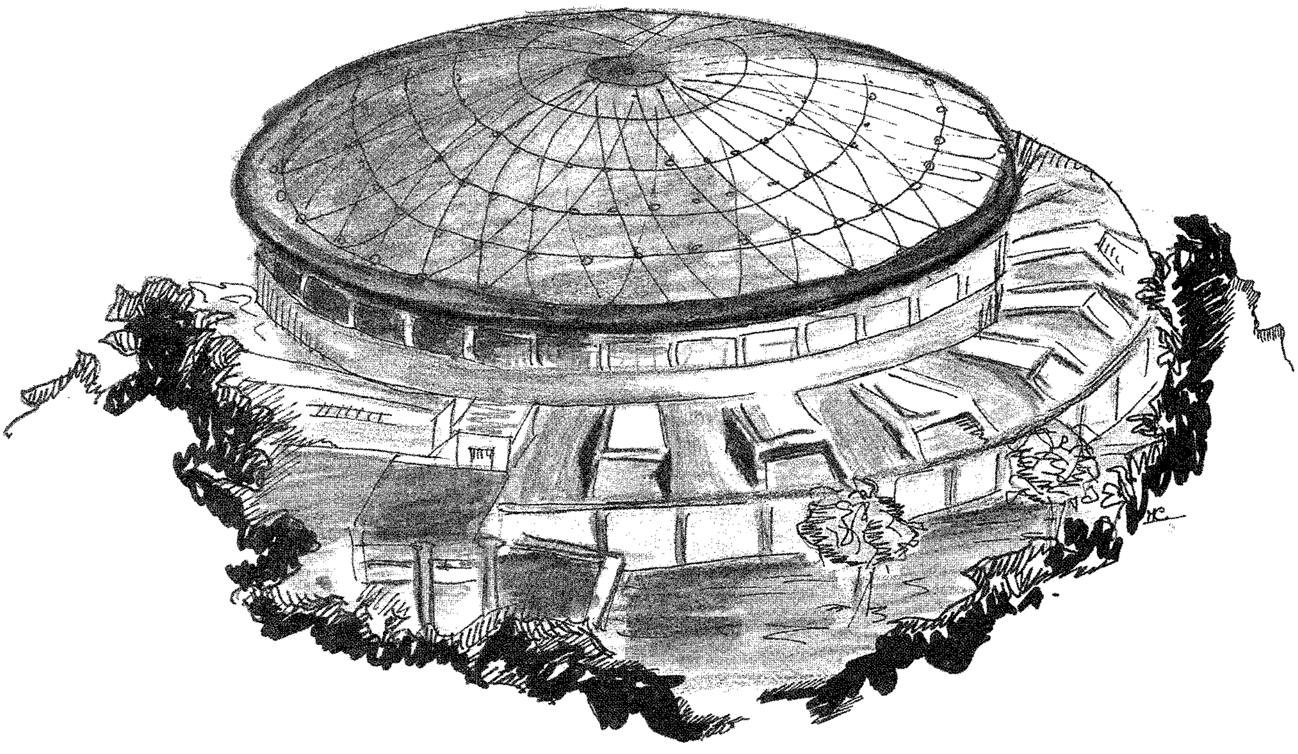

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ABSTRACT

The project of a new metropolitan area network using single mode optical fibers as physical medium, is presented. It supports transmission speeds higher than 100 Mbit/s (upgradable to a few Gbit/s) and allows to interconnect stations spreading over tens of kilometers. Its basic topology is a star that can be implemented using a passive N × N star coupler or a pair of N × 1 star couplers connected through an optical repeater. This second solution increases the number of stations and/or the area covered by the network. The medium multiple access scheme is

based on a deterministic algorithm handled by a central controller which communicates with the single stations through physically separated optical links. With this mechanism the efficiency of the network is not heavily dependent on the star radius.

1. - INTRODUCTION

The needs of networks with very high transmission speed for applications spreading from bulk data transfer to real-time data control are rapidly increasing. This demand implies the need of high bandwidth channels (e.g. optical fibers) and the development of new protocols in order to assure performances better than conventional local area networks (LANs).

Three different kinds of LAN protocols have been defined by the IEEE standard organization: IEEE 802.3 (a bus utilizing CSMA/CD as the access method) [1], IEEE 802.4 (a bus utilizing token passing as the access method) [2], IEEE 802.5 (a ring utilizing token passing as the access method) [3]. All of them have been adopted by the ISO/OSI standard organization, defining levels 1 and 2 of their reference model [4]. The interface to the higher software level is accomplished by means of a common logical link control (LLC) sublayer [5] defined on top of level two. A fourth LAN protocol, the ISO 8802/7 (a ring utilizing slotted ring as the access method) [6] is under definition. The token passing bus or ring protocols, as defined by IEEE, could still be used when the transmission rate increases to hundreds of Mbps, and/or the ring or bus length increases up to tens of kilometers, but in that case, the performances gradually deteriorate. For this reason, a new ANSI network protocol standard, FDDI [7], has been defined modifying the token releasing mechanism used in IEEE 802.5. FDDI runs at 100 Mbps and uses a second ring at a lower speed in order to close the ring in case of failure. FDDI allows to increase network dimensions and number of stations with good performances [8]. Better performances could also be obtained [9] by modifying the token reservation priority scheme defined by FDDI. Networks using token mechanisms include active processing components on each station, thus suffering by throughput and reliability constraints.

A second class of networks using only passive components has been considered (e.g. ExpressNet, D-Net, Fasnet, etc.)[10] [11] [12] [13]. These networks define a bus topology where the stations are connected through passive taps and the protocol is implemented through an implicit or explicit token mechanism. Due to the optical signal attenuation at each station located between the source and the destination, these networks support only a limited number of stations. Using N equal taps of 1 dB optical attenuation in a dual bus topology configuration, only 10 stations could be connected to such a network if the total power margin is the optimistic value of 45 dB [14].

Passive networks can also be built with star topologies obtained using several transmissive optical power splitters that are inherently reliable and contain no electronic components [15] [16]. An extensive use of star network architecture improved star coupler manufacturing processes both for multimode and single mode fibers.

If high bandwidth optical fibers are used as physical medium, a network can offer some other services, such as voice and video, in addition to file transfer and to real-time data control. A new class of LANs allowing this integration of services is currently under study. The extension to a metropolitan area and usage of optical fibers brought to define MANs (metropolitan area networks). MAN protocols cannot be a simple extension of LAN protocols, because physical medium, topology, and medium access control protocol are strongly correlated.

Currently different concepts are under discussion to propose standard protocols for MANs, for instance the Queued Packet and Synchronous Switch (QPSX) [17], the hybrid Fiber Distributed Data Interface (FDDI-II) [18], and the Multiple Slot and Token protocol (MST) [19]. The FDDI-II network defines a Hybrid Ring Controller capable of merging circuit and packet switched traffic. A Cycle Master initiates every 125 μsec a cycle where bandwidth of 6 Mbps (until a maximum of 16) can be reserved for "circuit-switched" traffic and the rest can be used for "packet-switched" traffic. QPSX also integrates circuit and packet switched traffic. The topology is defined by two active rings: each station connected to each ring can transmit on a ring and receive from the other. A central controller creates a cycle every 125 μsec. The Distributed Queuing Protocol [20] is implemented, each station counts the channel reservation requested from the preceding stations and manipulates internal counters in order to know where a free slot can be obtained.

In this paper the authors present a new MAN model allowing very high transmission speed (more then 100 Mbit/sec), which is capable to interconnect objects tens of kilometers apart. For this purpose, a new medium access control protocol is under development, compatible with the LLC software interface the ISO/OSI 8802/2 specification [5]. This network, which is STARNET, uses single mode optical fibers as physical medium, and interconnected passive optical star couplers as topology.

The main characteristics of STARNET can be summarized as follows:

1- easy insertion/deinsertion of stations in the network

2- high throughput and low delay (high efficiency)

3- active stations served in a round robin way, ordered according to topological parameters

4- hardware/software easily implementable protocol

A first physical implementation of the network is under development. The integration of video and voice traffic in the STARNET protocol will be object of a second stage of study.

This paper is divided as follows: STARNET physical medium, topology and protocol are described in paragraph 2. In paragraph 3 the maximum number of stations will be calculated taking into account the optical power margin and using completely passive NxN stars or two Nx1 stars interconnected by a repeater. In paragraph 4 the typical STARNET acces delay will be calculated and limits on the number of stations supported by STARNET will be given in the case of bounded access delay, while in paragraph 5 protocol simulations will be presented in order to estimate the protocol efficiency. Finally, paragraph 6 gives an overview of a first implementation design.

2. - TOPOLOGY AND PROTOCOL

Configuring STARNET, optical fibers have been chosen as physical medium because of their well known advantages: low loss, low dispersion, low cost, large bandwidth/Km, immunity against electro-magnetic interferences. Since active elements reduce network reliability, their usage is minimized in STARNET: passive optical star couplers are used in order to connect

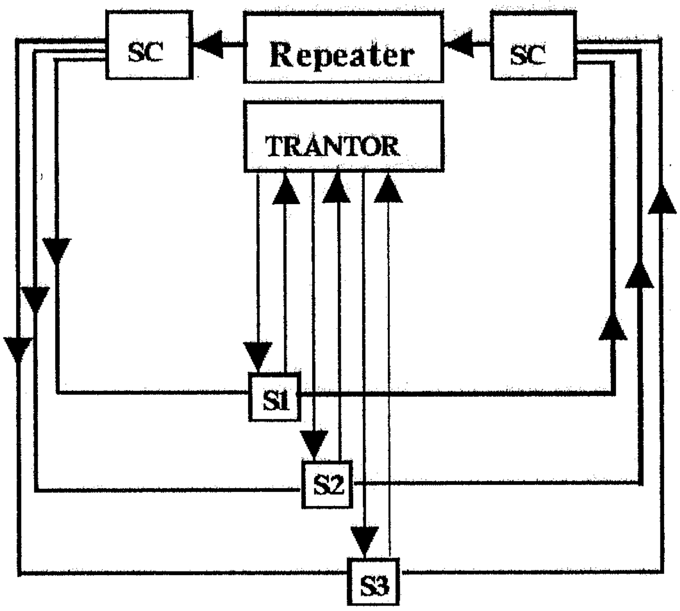

Figure 1. Basic STARNET topology

stations to the network and single mode optical fibers have been chosen instead of multimodal fibers because of their lower attenuation.

The basic STARNET topology is based on a NxN passive star coupler or a pair of Nx1 stars connected by a repeater (Fig.1). Each station is connected to the star using two fibers (transmitter and receiver) creating a flooding configuration (i.e., only one station at a time can transmit over the data channel and everybody else must listen).

The bandwidth allocation mechanism inside a star is handled by a central controller (TRANTOR, Transmission and Reception Analyzer and Network Traffic Organizer of Resources) which dialogues with the single stations through physically separated fiber optic links. The control channels must carry a very limited amount of information, so their transmission rate can be slower than the data channel rate, and therefore the hardware implementation can be cheap.

Splitting data and control over two independent communication structures allows packets lined head to tail in the center of the optical star. This increases the bandwidh utilization in a very efficient way, even if it increases the number of fibers. This is not as big a problem as it would seem, since the cost of an installed transmission cable changes very little with the actual number of fibers it contains. Each station, wanting to send a message, asks permission to the TRANTOR on its private control channel (Request To Send, RTS). This request message contains the length of packets to be transmitted. The station enters a wait state until a CTS (Clear to send) message is received. TRANTOR knows some configuration parameters: distance between each station and the star coupler, distance between each station and TRANTOR, station reaction times, guard times. Using this data, the central controller is able to calculate when the CTS message has to be sent to each station. The mechanism is described in the following (see Fig.2).

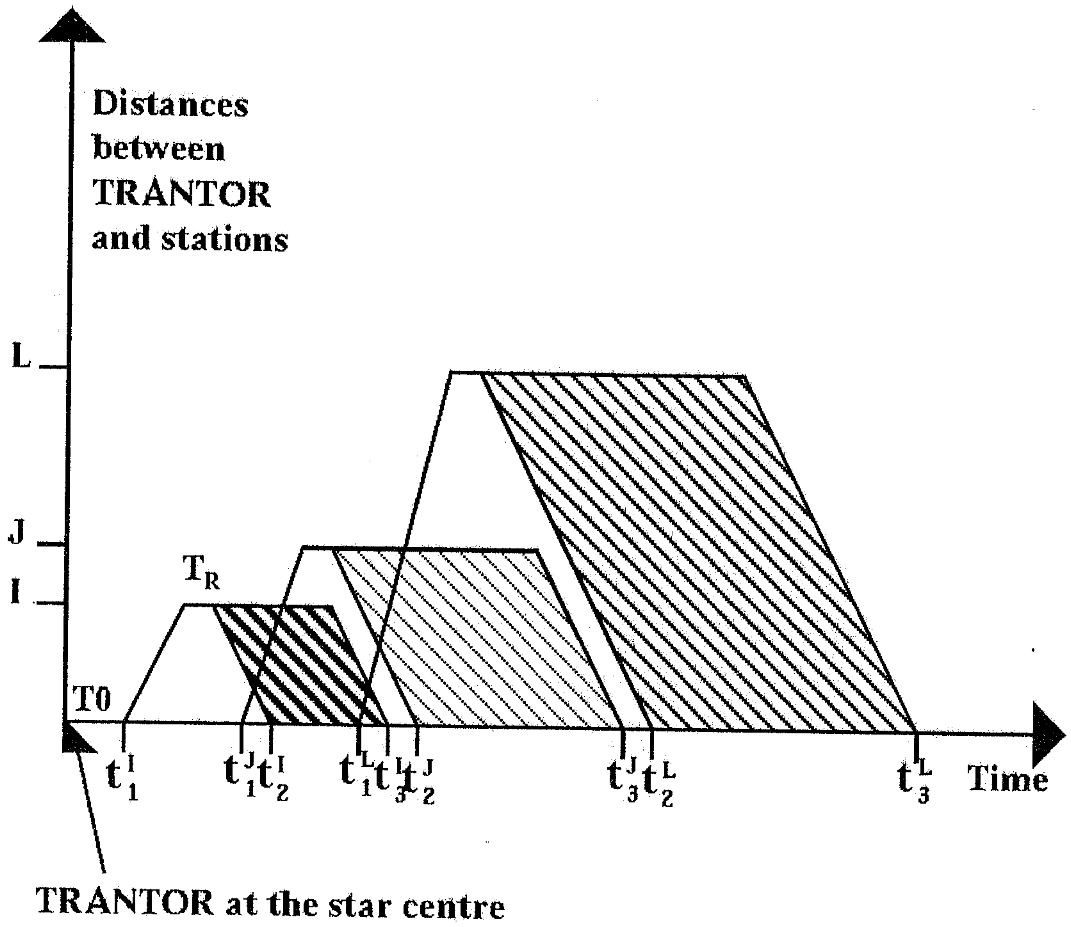

Figure 2. Packets lined head to tail in the center of the optical star

After an initial configuration time, when at least a channel reservation has been received, TRANTOR starts the authorization cycle, sending to the I^{th} station, at t_1^I time, the CTS message. The head of the message transmitted by the I^{th} station arrives to the star hub at t_2^I and the tail of message at t_3^I. For simplicity in the representation the TRANTOR module is supposed to be located in the star hub.

Let $T_I = t_3^I - t_2^I$ the packet transmission time (in μsec) for the I^{th} station. Let T_{guard} the minimum interpacket gap (in μsec) due to hardware requests and indetermination on the parameters implied in the calculations. Let d_I the distance (in kilometers) between the I^{th} station and the controller. This implies that $t_2^I - t_1^I = T_R + 2 * \tau * d_I$ μsec, where $\tau = 5$ μsec/Km is obtained from a value of 2×10^5 km/sec for the light speed inside the optical fiber and T_R is the reaction time of the I^{th} station, considered the same for all the stations in the star.

In order to calculate the time t_1^J (or the equivalent value of $\delta_t^J = t_1^J - t_1^I$), when the TRANTOR must send the CTS message to the J^{th} station transmitting after the I^{th} station, the following equation can be written assuring that no collisions will occur in the star hub.

$$\delta_t^J + T_R + 2 * \tau * d_J = T_R + 2 * \tau * d_I + T_I + T_{guard}$$

that gives

$$\delta_t^J = 2 * \tau * (d_I - d_J) + T_I + T_{guard} \tag{1}$$

In order to minimize the time wasted at the beginning of each authorization phase, the first station that is authorized to transmit is the nearest one. Some extra time can be lost if δ_t in (1) is negative. This implies that sometimes, and only for the earliest packets transmitted during a cycle, the distance between two packets in the data channel will be greater than the T_{guard} time.

If N stations had reserved the channel, the time cycle will be given by

$$T_{cycle} = T0 + T_R + 2 * \tau * d_1 + \sum_{i=1}^{N} (T_i + T_{guard}) + \sum_{j=2}^{N} \eta^j \tag{2}$$

where $\eta^j = -\delta_t^j$ for $\delta_t^j < 0$ and $\eta^j = 0$ in the other cases. T0 is the initial TRANTOR time that will be discussed in the following.

Each station can make a new reservation at the end of the transmission of its own packet (or during transmission if a double buffer exists). TRANTOR memorizes the new requests that will be served in the following authorization cycle. The protocol does not privilege any station, i.e. each station must be able to transmit during each authorization cycle. Therefore, TRANTOR has to wait in order to allow the last transmitting station to make a reservation for the next cycle. This time, that could be negligible if a double buffer exists in the station, must be included in the T0 time.

Evaluations of the different parameters involved in the T_{cycle} calculation will be given in paragraph IV.

The S(N) channel utilization when i stations are active is calculated as follows:

$$S(N) = \frac{\sum_{i=1}^{N} T_i}{T_{cycle}} \tag{3}$$

Two important conclusions can be now given: first of all, the STARNET efficiency at high and light loads depends only on the number of stations transmitting in each cycle and is independent of the number of stations in the network. Moreover, the efficiency depends only on the average distance between the stations and the star hub and is independent from the total round trip propagation delay as in protocol networks using implicit or explicit token algorithms.

3. - MAXIMUM NUMBER OF STATIONS

An important parameter of a passive fiber optic network architecture is the maximum number of stations that can be connected to it. It is well known that light detectors use much more signal power than their electronic counterparts.

To determine the maximum number of stations that can be supported, we must require that the signal transmitted by the light source is properly detected at the end of the longest network path by the light detector.

Some easy calculation can be made for a NxN star using the following definitions:

1- M : power margin (typically 30-40 dB). It is defined as the difference between the laser output power (in dBm) and the minimum power detectable at the light detector (in dBm);

2- SC : star coupler loss (in dB);

3- α: optical fiber loss (typically 0.5 dB/km for single mode fibers);

4- L : star radius (in km);

5- ST : station connection loss (typically 1 dB).

Using these parameters, the following relation can be written for STARNET:

$$2 * \mathrm{L} * \alpha + \mathrm{SC} + 2 * \mathrm{ST} \leq \mathrm{M} \tag{4}$$

SC is the sum of two contributions, excess loss (EL) and insertion loss or power splitting (IL) , defined as:

$$\mathrm{EL} = 10 \log_{10}(\mathrm{P_i}/(\mathrm{P_{i1}} + ... + \mathrm{P_{iN}})) \tag{5}$$

$$\mathrm{IL} = 10 \log_{10}(\mathrm{P_i}/\mathrm{P_{ij}}) \tag{6}$$

where $\mathrm{P_i}$ is the input power at port i, $\mathrm{P_{ij}}$ is the relative power at output port j, and N is the number of ports.

Obviously, for a given port i,

$$\mathrm{ILmax} = 10 \log_{10}(\mathrm{P_i}/\mathrm{P_{ij}min}) \tag{6b}$$

The production process of the biconically tapered fiber star coupler [21] is able to minimize output power deviations, allowing to approximate the excess loss for a NxN star coupler by the following expresion,

$$\mathrm{EL} = \log_{10}(\mathrm{N}) \tag{7}$$

If $\mathrm{P_{ij}} = \mathrm{P_{ik}}$ for each i, j and k, then the star coupler loss can be aproximated by

$$\mathrm{SC} = 11 \log_{10}(\mathrm{N}) \tag{8}$$

Different topologies are examinated in the following either for passive configuration or introducing an optical repeater. In each case the maximum star radius (L_{max}) will be given as a function of the number of stations (N) and of the optical power margin (M). The results are presented in Table 1.

Table 1 — Maximum star radius as a function of number of stations and power margin

N	(a) NxN star M=40/30dB Lmax(Km)	(b) Nx1-1xN without repeater M=40/30dB Lmax(Km)	(c) Nx1-1xN with repeater M=40/30dB Lmax(Km)
4	31/21	24/14	62/42
8	28/18	18/ 8	56/36
16	24/14	11/ 1	49/29
32	21/11	4/ -	42/22
64	18/ 8	-/ -	36/16
128	14/ 4	-/ -	29/ 9
256	11/ 1	-/ -	23/ 3
512	8/ -	-/ -	16/ -

Column (a) is obtained from (4) using a power margin of 40 and 30 dB respectively In order to increase the number of stations supported without reducing the star radius, a differen topology could be used creating a NxN star from two Nx1 stars connected through a repeate Columns (b) and (c) present respectively the results obtained using the following expressio for a completely passive Nx1-1xN stars configuration,

$$2 * L * \alpha + 2 * SC + 2 * ST \leq M \tag{9}$$

or the following expression introducing an active repeater between the two stars,

$$L * \alpha + SC + 2 * ST \leq M \tag{10}$$

In each case, the repeater connection loss is assumed to be comparable to the station connection loss, the repeater optical power output is the same as the stations, and expression (8) is supposed to be still valid for the total coupler loss for a Nx1 star coupler.

It is obvious from the previous calculation that it is impossible to set up a star MAN without introducing active repeaters, unless accepting strong limitations on the number of stations and on the maximum distances between the stations and the star hub.

4. - ACCESS DELAY

Access delay in STARNET may be defined as the interval between the time when a packet is ready for transmission in the station buffer and the time when it is actually transmitted. The average access delay in STARNET corresponds to the average cycle time when only a buffer per station exists.

In the previous paragraph, it has been shown that for each configuration the maximum number of stations and the maximum star radius are dependent on each other. The maximum number of stations also depends on the access delay when it needs to be bounded in order to allow some particular applications.

Guaranteed delay is of concern because a MAN must be prepared to carry different kinds of traffic such as: low throughput- high delay (i.e., interactive), low throughput- low delay (i.e., file transfer), low throughput- bounded delay (i.e., voice), high throughput- bounded delay (i.e., video), and others. If the access protocol offers a bounded delay, the bandwidth allocation mechanism is greatly simplified.

For example, if only one station wants to transmit and all the other stations remain silent, the waiting time T_w for such a station is

$$T_w = 2 * \tau * L + T0 + T_R \tag{11}$$

where L is the distance (in km) between the station and the star hub, and T0 and T_R are the time lost by TRANTOR and Station repectively.

If several stations transmit during the same cycle, the total cycle time will be given by the expresion (2) where N is now the number of "active" stations.

In the following, some considerations about the parameters concurrent to the T_{guard}, T0 and packet length calculations will be given. As far as the T_{guard} value is concerned, two parameters are taken into account:

1. Laser power on and off times. Star configuration requires that in order to reduce noise, each station must turn off the laser standby output power at the end of the packet transmisssion. In the efficiency calculation this times are assumed to be 300 ns each.
2. Indetermination on the distance measurement. Actualy OTDR instrument are able to measure distances in a large range with a precision better than 10 m. Since four distances are implied in the TRANTOR analysis, this indetermination contributes 200 ns to the T_{guard} calculation.

Table 2 — Number of stations as a function of the average star radius and transmission speed, for a total cycle time bounded to 8 msec

L (Km)	0.1Gbps 2 KBytes N	0.1Gbps 4 KBytes N	1Gbps 2 KBytes N	1Gbps 4 KBytes N
5	49	24	470	241
10	49	24	467	239
15	48	24	464	238
20	48	24	461	236
25	48	24	458	235
30	47	23	455	233

Concerning the T0 calculation, this time must allow the initialization of timers that will start the following CTS messages cycle. The time requested for the first CTS message transmission (about 2 bytes packet lenght) is also included. A value of $T0 = 6$ μsec (equivalent to 40 CPU cycles of 100 ns, 1 μsec of CTS transmission and reception time, and 1 μsec for the last station reservation time) is used in the calculation.

Concerning the T_R factor, this time is fixed to 200 ns (2 CPU cycles) supposing a dedicated CPU, while concerning the packet length, the maximum value depends on the maximum delay requested.

Public voice services require at least a 64 Kbit/sec data rate and a maximum access delay of 8 ms. In order to provide access delay better than this limit, if STARNET must support also this kind of traffic, the maximum number of stations supported by the network obtained from (2) in the case of equal distances, are presented in Table 2, considering different packet lengths (2k and 4k bytes) and two different transmission rates (0.1 Gbps and 1 Gbps).

From the above data, we conclude that also at very high load, and without introducing special priority mechanisms, the actual STARNET protocol provides a bounded delay when a high number of stations are connected.

Comparing with the results presented in Table 1, we conclude that for speed about 0.1 Gbps no repeaters are required configuring a network with a bounded cycle delay. Configurations at 1 Gbps requires repeaters in order to allow a greater number of stations in the network.

5. - PROTOCOL SIMULATION

Montecarlo simulations of a STARNET star have been studied under different traffic conditions.

Two new parameters are introduced in the efficiency calculation: The initial preamble that will allow clock recovery at the receiving station and the final packet flag. Supposing that the system works with a parallel/serial conversion of 32 bits, this fields are supposed to be 32 bits long. The encoder scheme (8B/10B in the actual project) is not taken into account.

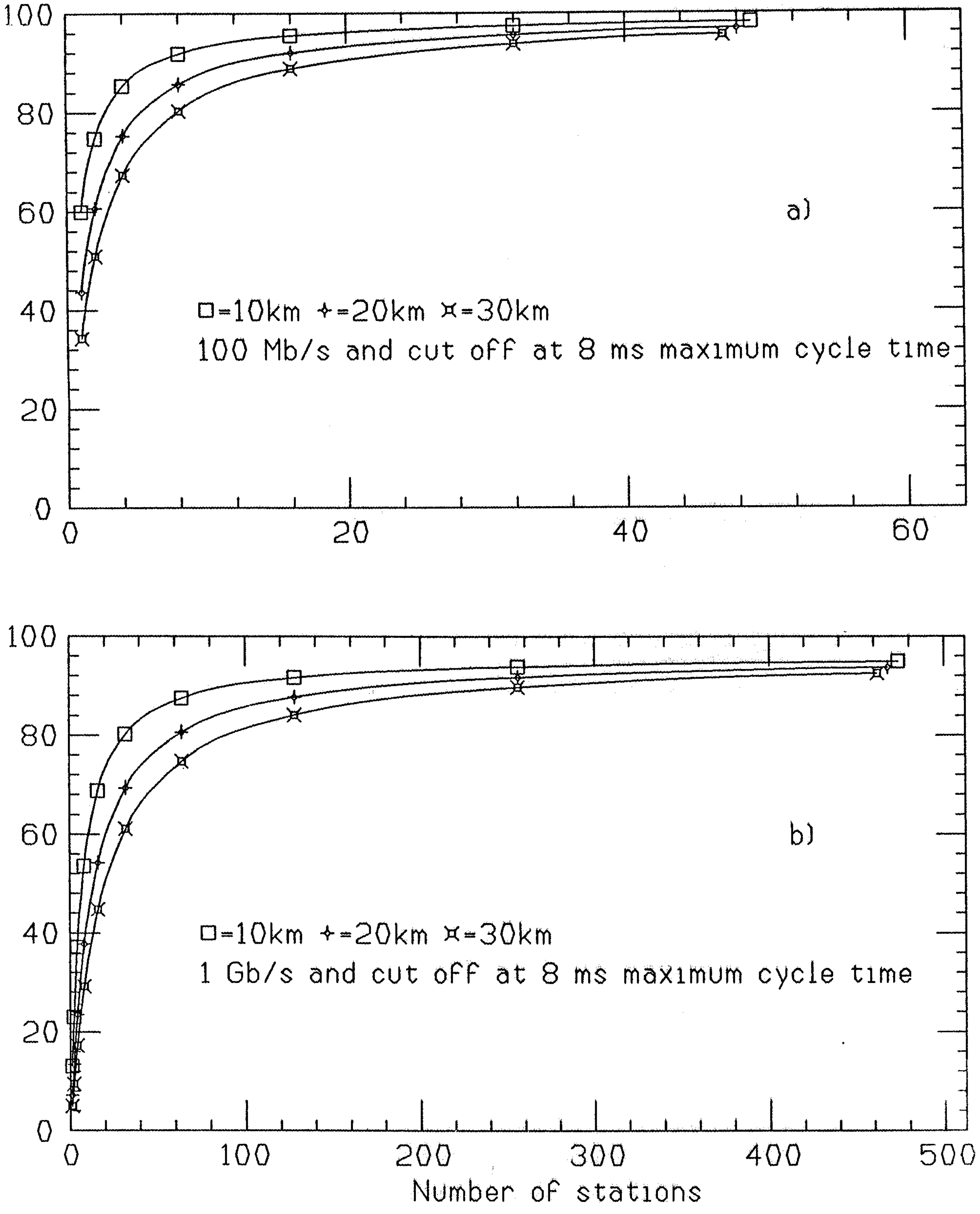

Figure 3. STARNET efficiencies for different star radius

Fig.3 presents the STARNET cycle efficiency as a function of the number of "active" stations in the star transmitting 2K bytes packets, as a function of the star radius for a channel speed of 0.1 Gbps (a) and 1 Gbps (b). The maximum number of stations is calculated for a maximum cycle time of 8 msec.

6. - PROTOTYPING STARNET

The design of a first STARNET prototype with speed over 100 Mbit/s is under development. A first TRANTOR unit capable of handling the reservation mechanism for up to 8 stations is being implemented using a DSP central processor. A serial-to-parallel and parallel-to-serial converter has been implemented, together with a clock recovery circuit and an encoder-decoder, for an optical interface to the line. A station controller implementing CRC diagnostic, packet buffering, address recognition and interface toward the central controller (TRANTOR) is in an advanced state of design.

CONCLUSIONS

We have presented the model of a MAN featuring high efficiency in channel utilization and low delay using a simple star topology over long distances. This is achieved through the use of a control channel separate from the data channel.

An extension to multiple stars using distributed controllers or bridges is under study.

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