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FATHOC - a rate control algorithm for HFC networks

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Abstract

This paper presents a rate control algorithm to use with SARP (Simple ATM based Reservation Protocol) for HFC (Hybrid Fibre Coax) networks. The SARP is a hybrid reservation and rate based protocol, based on ATM, whose main characteristics are its simplicity, high efficiency, and flexibility to support different classes of traffic. FATHOC (Fairness Achievement Through Congestion) deals with fairness achievement and congestion avoidance problems as a single problem, by trying to achieve fairness dynamically through congestion handling. FATHOC scope of application is both the ABR and nrt-VBR service categories. FATHOC algorithm was designed to work on HFC networks at the Head-end and was developed in the scope of the project ATHOC, a European ACTS research and development project.

Keywords

ATM, ABR, nrt-VBR, Hybrid Fibre Coax, medium access protocols

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1 INTRODUCTION

FATHOC (Fairness Achievement Through Congestion) is an algorithm for ABR rate control, and also for nrt-VBR, that achieves fairness and avoids congestion, in a new way, i.e., by trying to achieve fairness dynamically through congestion handling.

FATHOC initial design goal was to schedule the transmission grant rates of continuous type connections present on the upstream digital channel of an HFC network. Located at the Head-end of HFC networks, it implements the switch behaviour for the ABR service (ATM Forum, 1996), and can also be used on the computation of the transmission grant rates of nrt-VBR sources. FATHOC was designed to be compatible with SARP (Simple ATM based Reservation Protocol) for HFC (Hybrid Fibre Coax) networks (Sierens, 1996) (Nunes, 1996), but its scope of application may be extended to any other protocol.

SARP is a hybrid reservation and rate based protocol, based on ATM, whose main characteristics are its simplicity, high efficiency, and flexibility to support different classes of traffic (CBR, VBR, UBR, ABR), in different combinations. Two types of sources are considered for the SARP scheduling in the upstream channel: continuous sources (corresponding to CBR and VBR audio and video sources), and bursty traffic sources (UBR and ABR, e.g., LAN type traffic).

For the first kind of sources, the SARP uses a rate-based and dynamic scheduling protocol, and the adjustment of the allocated bandwidth to each terminal is based on implicit feedback of the terminal activity. The Head-end monitors the source activity based on the transmission queue piggybacked on the transmitted cells of the terminal and also by detecting empty cells (Macedo, 1997). For the second type of sources, the protocol is based on a request/credit method, using contention mini-slots.

Transmission of ATM cells on the upstream channel is allowed by the corresponding transmission grants given to each terminal on the downstream slots.

2 VIRTUAL SOURCE / VIRTUAL DESTINATION OPERATION AT THE HEAD-END

For ABR sources, full compatibility with the ABR protocol is required, even considering the particular MAC level differences between HFC networks and common ATM networks. The main difference and the additional complexity derive from the fact that in the HFC networks, cells are allowed to be transmitted to the Head-end by transmission grants issued to the stations, instead of being transmitted by the initiative of the stations, as it happens on normal switches.

As a consequence of this specific characteristic of the HFC, the Head-end must know the true transmission rate of the source in order to allow the source to transmit data and also to save bandwidth, with a minimal number of generated empty cells. This is true either when the source is transmitting below the *CCR* (or *ACR*), or when a data burst stops. Also, as the total bandwidth is limited to the bandwidth of the upstream channel, it is important to limit the bandwidth given to the ABR sources, when higher priority sources demand additional bandwidth.

In order to implement the ABR service on the HFC bus, some problems must be addressed. They are:

- Fairness achievement and congestion avoidance schemes, for dynamic scheduling of the ABR sources.
- ABR re-scheduling when other higher priority classes (namely, rt-VBR) connections demand additional bandwidth.
- Implementation of use-it-or-loose-it policies for ABR sources, when they transmit at a rate lower than CCR or when they stop transmission.

After analysis of different alternatives, it was considered that the cleaner way to solve these problems was to implement the Virtual Source/Virtual Destination feature in the Head-end.

The Virtual Source/Virtual Destination feature operation proposed by the authors for the ATHOC project can be described as following:

- Each time a FRM cell arrives to the Head-end, coming from the terminal, fairness achievement and congestion avoidance computations are done by FATHOC and an Explicit Rate is computed.
- The values of the bits *CI* (Congestion Indication) and *NI* (Not Increase) and of *ER* (Explicit Rate), are combined with the values that came in the last BRM cell from the ATM network, and with the values computed at the Head-end. The results of these computations are registered at a BRM cell sent back to the terminal.
- The Head-end does also the Source Behaviour rate computations in order to estimate the new source *ACR*, and the transmission grant rate T_g to be given to the source. The FRM cell is then transmitted to the ATM network with the computed value for ACR, and the other fields kept unchanged.
- The Head-end can also do true rate estimation, based on the activity of the source, namely in order to detect burst stops of the ABR connections.
- The Head-end can also do true rate estimation, based on the activity of the source, namely in order to adjust to the true *ACR* of the source and to detect burst stops of the ABR connections.

For non ABR sources, namely for nrt-VBR sources, the operation of the Head-is simpler. Transmission rates given to the sources are calculated exclusively based on the contracted parameters of the connection, namely *PCR* (Peak Cell Rate), and the total bandwidth available for the nrt-VBR service. However, the same basic FATHOC fairness achievement and congestion avoidance scheme are applicable.

We now describe FATHOC operation for the ABR sources and after we describe also its possible implementation for nrt-VBR sources.

3 FATHOC ALGORITHM

FATHOC basic operational principle consists in allowing sources to get progressively more bandwidth, until a congestion state is reached, and to constrain progressively the sources that are using more bandwidth until the congestion state is over.

Two different control points are defined: *CongestionStateEntering* and *CongestionStateExiting*, corresponding to two different levels of total ABR bandwidth load.

The congestion state is reached when some sources demand extra bandwidth, because they are allowed by the ATM network to rise their rates. Constrain of the sources by FATHOC is then activated, and the sources that are using larger fractions of the total bandwidth, with respect to some fairness criterion, are forced to lower progressively their rates.

Congestion state is then exited, and constraints are progressively relaxed until another congestion state happens.

The fairness criteria can be equal share, equal share of the bandwidth left after satisfaction of minimum cell rate requirements of the sources, or any other.

In those congestion/non-congestion cycles, sources using lower bandwidth, with respect to the criterion, are always rising their rates, and fairness is naturally achieved. In steady state operation, i.e., when fairness is achieved and ATM network bandwidth constraints are stable, the ABR bandwidth load will typically oscillate between non-congestion and congestion states.

In this version of FATHOC, the criterion for fairness achievement is the *equal share of ABRCapacity bandwidth left after satisfaction of minimum cell rate requirements of all sources. ABRCapacity* is the target utilisation of the ABR service bandwidth quota.

FairShare can then be defined by expression

$$FairSharei = MCRi + \frac{ABRSharableCapacity}{NumberOfVCs} \tag{1}$$

where

$$ABRSharableCapacity = ABRCapacity - \sum_{j=1}^{NumberOfVCs} MCRj \tag{2}$$

However, the constraints on sources rates imposed by the ATM network (through *CI* and *NI* bits, and the *ER* field), or by low values of *PCR*, can lead to the existence of sources with bandwidth shares lower than the *FairShare* value of expression (1). When this situation occurs, it is reasonable to allow other sources, not constrained by the ATM network, to get bandwidth shares higher than that *FairShare* value of expression (1), in order to achieve higher utilisation of the bandwidth quota assigned to the ABR services.

According to the criterion chosen for fairness, sources that are not constrained by the ATM network, should be permitted to share equal fractions of *ABRCapacity* minus the sum of the *MCR* (Minimum Cell Rate) requirements of all ABR sources and minus the sum of the cell rates of all sources that are constrained by the ATM network to cell rate values lower than the *FairShare* value of the expression (1). Such a reasoning is similar to that of the MIT scheme (see Jain, 1996a) for which the value of *FairShare* is given by the expression:

$$FairShare = \frac{LinkBandwidth - \sum BandwidthOfUnderloadingVCs}{NumberOfVCs - NumberOfUnderloadingVCs}$$

and that is used by several algorithms, namely by ERICA (Jain, 1996b) (Jain, 1996c).

This new extended criterion means that in FATHOC the true value for *FairShare* for unconstrained sources, when the ATM network constrains some sources to bandwidth uses lower than that given by *FairShare* value of the expression (1), is given by expression

$$FairShare_i = MCR_i + \frac{ABRCapacity - \sum_{i=1}^{NumberOfVCs} MCR_i - \sum_{i=1}^{NumberOfConstrained} (CCR_i - MCR_i)}{NumberOfVCs - NumberOfConstrained} \qquad (3)$$

Now, we explain the way FATHOC achieves this new fairness criterion and avoids congestion.

In FATHOC algorithm, a factor is defined for each source *i*, $ShareFactor_i$, whose meaning is the ratio between each fraction of the *ABRSharableCapacity* used by the source and the value of *FairShare* if no sources were constrained by the ATM network. For each source *i*, $ShareFactor_i$ is given by

$$ShareFactor_i = \frac{(CCR_i - MCR_i)}{ABRSharableCapacity \big/ NumberOfVCs} \qquad (4)$$

Also, a global *ShareFactor* is defined, with the meaning of the maximum possible value of all $ShareFactor_i$. It is upon global *ShareFactor* that FATHOC acts to achieve fairness and avoid congestion. Therefore

$$ShareFactor = \max \,\&\, \text{bound}\,(ShareFactor_i) \qquad (5)$$

When a congestion state is entered, *ShareFactor* is set to the maximum of the calculated *ShareFactor*$_i$, and then progressively lowered with some decay rate. This procedure has the effect of reducing the cell rates of sources using higher bandwidth, with respect to the fairness criterion, i.e., those sources that have higher *ShareFactor*$_i$, and of reducing the total ABR bandwidth load, forcing exiting the congestion state. However, sources using less bandwidth, i.e. the sources with *ShareFactor*$_i$ lower than the global *ShareFactor*, can acquire more bandwidth, with the condition of their *ShareFactor*$_i$ not surpassing the global *ShareFactor*.

When the congestion state is exited, the global *ShareFactor* is allowed to rise, relaxing the bandwidth use. Sources that are not constrained by the ATM network, are permitted to acquire progressively higher fractions of the ABR bandwidth quota.

These procedures can be seen on figure 1, which shows the full FATHOC pseudo-code.

EnteringCongestionStateLoadFactor and *ExitingCongestionStateLoadFactor* are respectively the load factors for entering and exiting congestion state. In our simulations they were set to 91.25% and 90% of ABR bandwidth target utilisation.

The algorithm parameters *DeltaIncrShareFactor* and *DeltaDecrShareFactor* are respectively the increment and decrement to be given to ShareFactor each time a FRM cell arrives to the Head-end, when the Head-end is on a non-congestion or on a congestion state, respectively.

The decrement *DeltaDecrShareFactor* means that *ShareFactor* falls down from *MaxShareFactor*, i.e., the maximum of the *ShareFactor*$_i$ of all active ABR sources when congestion state is entered, until the (*MaxShareFactor*-1) value, in a calculated number of FRM cells, dependent on the number of the active sources. *ShareFactorIncrRate* means that *ShareFactor* increases its value by 1 (one) in a given number of FRM cells, also dependent on the number of active sources.

4 FATHOC TUNING

Tuning of FATHOC algorithm parameters *DeltaIncrShareFactor* and *DeltaDecrShareFactor* can be done taking into account the dynamic behaviour of ABR sources.

The number of active sources can vary strongly. If the *DeltaIncrShareFactor* is made independent of the number of active sources, *NumberOfVCs*, some problems could arise. For instance, if the number of sources is high, the increase of *ShareFactor* could be done after a low number of FRM cells compared with the total number of active sources, meaning that congestion could be entered quickly with few sources having their rates increased.

If we make *DeltaIncrShareFactor* dependent on the inverse of the number of active sources, we can reduce that effect, and all sources are allowed to increase progressively their rates. However, if the number of sources increase, *ShareFactor* will also increase more slowly, but it is also true that perturbations on the constraints of individual sources will have less importance on the overall bandwidth utilisation. Therefore it is reasonable to make *DeltaIncrShareFactor* dependent on the inverse of the number of sources.

```
FATHOC ALGORITHM

Initialisation
    ShareFactor = 1;
    congestion = false;

if FRM cell from any source i
    if not congestion
        if LoadFactor >= EnteringCongestionStateLoadFactor
            calculate MaxShareFactor = max of ShareFactor_i ;
            ShareFactor = MaxShareFactor;
            calculate DeltaDecrShareFactor;
            congestion = true;
    else
        if LoadFactor < ExitingCongestionStateLoadFactor
        calculate DeltaIncrShareFactor;
        congestion = false;

    if congestion
        ShareFactor = ShareFactor - DeltaDecrShareFactor ;
    else
        ShareFactor = ShareFactor + DeltaIncrShareFactor ;
    ER_Head-end i =  MCR_i +
              ShareFactor * ABRSharableCapacity / Number of VCs ;

    /* The ER transmitted to terminal is the minimum value of ER_Head-endi
    and the ER that has come on a BRM cell from the ATM network */
```

Figure 1 Pseudo-code of the FATHOC algorithm

Similar reasoning can be made for *DeltaDecrShareFactor*.

Tuning of *DeltaIncrShareFactor* and of *DeltaDecrShareFactor* can be made such that

$$DeltaIncrShareFactor = \frac{1}{N_{\mathrm{FRMi}}\ Number\ of\ VCs} \tag{6}$$

$$DeltaDecrShareFactor = \frac{MaxShareFactor - 1}{N_{\mathrm{FRMd}}\ NumberOfVCs} \tag{7}$$

In expression (7), N_{FRMi} and N_{FRMd} are the mean number of FRM cells, received per virtual channel, calculated to produce the dimensioned *ShareFactor* changes, respectively 1 and (*MaxShareFactor*-1) for non-congestion and congestion states. These numbers of FRM cell cycles are dimensioned, taking into consideration the dynamic behaviour, but also admissible numbers.

We can limit the rise time from a non-congestion state to a congestion state to a maximum value (e.g. 150 ms), and the maximum fall time from a congestion state to a non-congestion state to another maximum value (e.g. 100 ms). Naming the rise and fall times respectively by τ_i and τ_d, we have N_{FRMi} and N_{FRMd} given by the following expressions

$$N_{\mathrm{FRMi}} = \frac{ABRCapacity\ \tau_i}{(NRM + 1)\ C_l\ NumberOfVCs} \tag{8}$$

$$N_{\mathrm{FRMd}} = \frac{ABRCapacity\ \tau_d}{(NRM + 1)\ C_l\ NumberOfVCs} \tag{9}$$

where *NRM* is the number of data cells between two FRM cells, and C_l is the cell length in bits.

However, we also limit those values to admissible values of

$$3 \leq N_{\mathrm{FRMi}} \leq 6 \tag{8a}$$

$$3 \leq N_{\mathrm{FRMd}} \leq 6 \tag{9a}$$

Doubling *ShareFactor* will be limited to a minimum of 3 FRM cycles and to a maximum of 6 FRM cycles. Halving the extra value above 1 of *ShareFactor*, will be limited to a minimum of 3 FRM cycles and to a maximum of 6 FRM cycles. For low *NumberOfVCs* that values fasten the non-congestion/congestion cycles, with respect to the cycles obtained with the former N_{FRMi} and N_{FRMd} values of expressions (8) and (9), while for high *Number of VCs* they shape the way *ShareFactor* is increased and decreased.

5 SIMULATION RESULTS

We have made several simulations of the FATHOC algorithm with ABR continuous sources. Simulations were run with a bus length of 40 km and 10 Mbps for the ABR bandwidth quota. The target utilisation was 90% of that value, meaning that *ABRCapacity* will be 9 MBps.

The load factors *EnteringCongestionStateLoadFactor* and *ExitingCongestionStateLoadFactor* were set respectively to 91.25% and 90% of *ABRCapacity*. The *DeltaIncrShareFactor* and *DeltaIncrShareFactor* values were those given by expression (8), (8a), (9), and (9a).

In the first simulation, we show how FATHOC achieves fairness and avoid congestion, and how the fairness criteria used is met. The simulation was done with six ABR sources. The first three have *MCR* = 100 Kbps and the last three have *MCR* = 500 Kbps. All sources have *PCR* = 12 Mbps, and begin at $t = 0$ ms. The duration of all simulations was 1.5 s. Figure 2 shows the results of the first simulations.

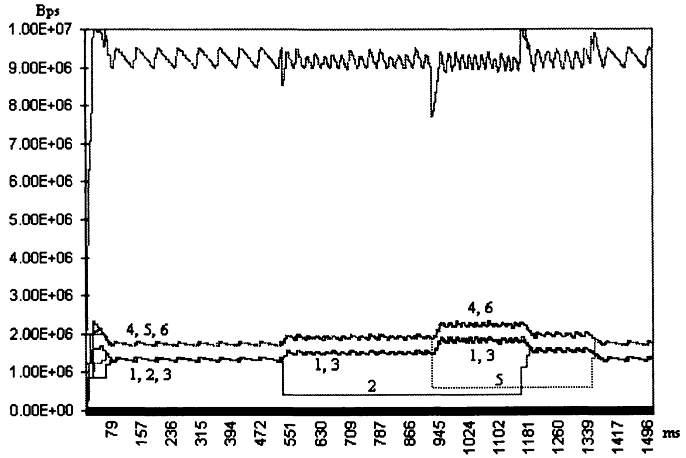

Figure 2 Simulation with different *MCR* and constraints on source rates

Note that source 2 and source 6 experienced constraints from the ATM core network. Source 2 between $t = 500$ ms and $t = 1.1$ s with *ER* = 400 Kbps, and source 5 between $t = 900$ ms and $t = 1.3$ s with an *ER* = 600 Kbps.

As it can be seen, the criterion chosen for fairness works quite well, and sources share equal fractions of bandwidth above their *MCR*. Sources 4, 5 and 6 have transmission rates that are 400 Kbps higher than sources from 1 to 3. This results from the way the $ShareFactor_i$ are calculated by expression (4). Note that minimum cell rate (*MCR*) requirements are not considered in the computations. It can also be seen that, when constraints on the source rates are present, the other sources rise their rates, and the fairness criteria are still met.

The other three simulations were done to test the behaviour of FATHOC in the presence of an increasing number of sources. Simulations were done with five, ten, and twenty sources. Sources had *MCR* = 100 Kbps, *PCR* = 12 Mbps, and all began at t = 0 ms. Several constraints, that we do not enumerate here, were imposed to the sources transmission rates.

The results of the simulations are shown on figure 3, 4, and 5.

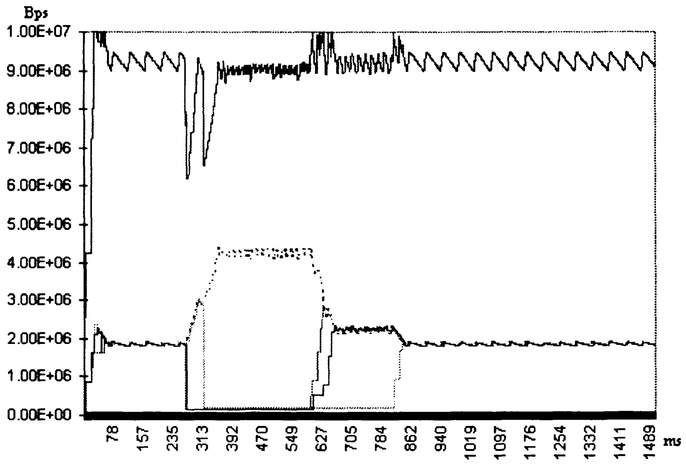

Figure 3 Simulation of FATHOC with five sources

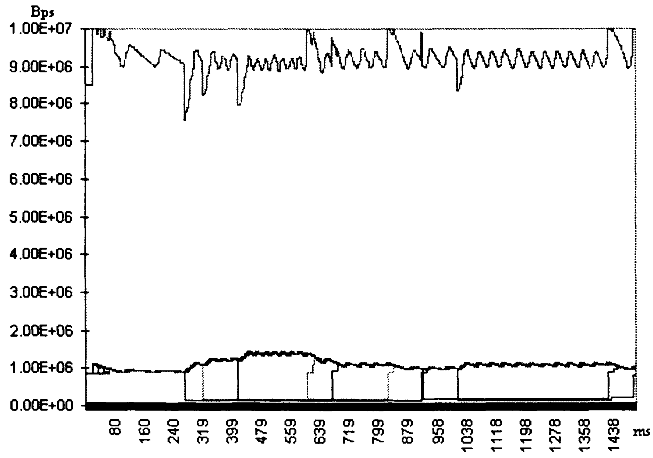

Figure 4 Simulation of FATHOC with ten sources

As can be seen, the sources that are not constrained by the ATM core network are led to share the bandwidth left available by the constrained sources. Sources transmission rates oscillations are small and decrease with the number of the active sources.

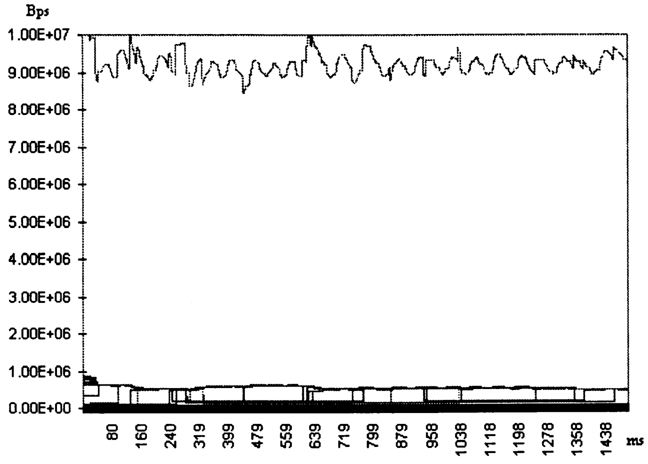

Figure 5 Simulation of FATHOC with twenty sources

6 ADAPTATION TO THE NRT-VBR CATEGORY SERVICE

Adaptation of FATHOC to nrt-VBR is simple. FRM cells does not exist, but an equivalent control interval can be easily implemented. In each control time interval, identification of non-congestion and congestion states and computation of *ShareFactor* and other algorithm parameters can be done with the same computations of the ABR version.

With nrt-VBR sources, the constraints on the transmission rates are the contracted *PCR* of the connections. When equal rate values for all sources are higher than the *PCR* values of some sources, this means that these sources are constrained, and the extra bandwidth is distributed by the sources with higher *PCR* values. It is worth noting that FATHOC was designed, not bearing in mind any specific service category, but only generic continuous type sources.

7 CONCLUSIONS AND FUTURE WORK

FATHOC is a simple algorithm for ABR fairness achievement and congestion avoidance applicable to HFC networks. Its computations are simple and very flexible to implement different fairness criteria. FATHOC can also be easily adapted to the nrt-VBR category service.

The basic FATHOC principle to achieve fairness is to let sources rise their rates until a congestion state is reached and then apply a criterion of fairness to decrease the rates of sources using more bandwidth, with respect to that criterion, until the congestion state is exited. In the congestion/non-congestion cycles, sources using more bandwidth give up bandwidth, and sources using less bandwidth acquire bandwidth, according with the developed algorithm.

FATHOC deals very well with constraints on source rates imposed by the ATM network. Unconstrained sources achieve naturally equal shares of the bandwidth left after satisfaction of minimum rate requirements, and of the constraints imposed to the source rates.

We also think that FATHOC computation framework is suitable to the application of control theory techniques. We have been working on a PID controller for FATHOC, but these investigations are still in a preliminary stage.

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