# An alternative WDM Architecture and a new MAC Protocol Analysis

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*Abstract:* - Since the electronic processing bottleneck that the single control channel architecture introduce is high, we propose a new WDM control architecture, for WDM star-coupled photonic networks, to overcome this problem. Also the proposed network architecture except for reducing the headers electronic processing bottleneck at each station, restricts data channel collision. We examine a network model of finite population. We develop a queueing model using discrete time Markov chains to evaluate the system performance. It is given a rigorous steady state analysis and the numerical results are presented for various number of stations and channels for comparison.

*Key-Words:*-wavelength division multiplexing WDM, Multichannel Control Architecture, receiver, electronic processing bottleneck, queueing model, Markov chain.

## 1 Introduction

Single-hop photonic networks suffer from limitations. The primary limiting factor is the speed mismatch between the optical and electronic components. The problem arises since the theoretical capacity of fiber optics is close to 75 Tbps while current electronics processing is limited to a few Gbps. The basic concept of WDM technology is the ability to simultaneously transmit data on multiple wavelengths on a single fiber. WDM networks provides a practical solution to the opto-electronic speed mismatch problem. A class of WDMA protocols based on pretransmission coordination employ a single separate common shared channel to exchange control information and the remainder channels are used as data channels. Thus for each packet on a data channel, a control packet is transmitted on the shared control channel, and each station is required to process all the control packets on the control channel. A fundamental problem in this protocol class is the ability of a station to receive and process all control packets that are transmitted over the single control channel. The maximum processing rate is limited to the speed of electronic interface of a station. This creates the electronic processing bottleneck [1-6].

Assume a system consisting of $M$ high speed bursty traffic stations, each transmitting at a Poisson mean rate $\lambda$ packets/sec. Thus each station must be able to receive and process from the single common control channel at processing rate $\Theta = \lambda M$ headers/sec. Assume a fixed rate of $\lambda$, then, as $M$ increases, $\Theta$ approaches a value that corresponds to the full interface electronic speed. We face the same problem as $\lambda$ increases with fixed $M$. From this point the electronic processing bottleneck begins.

This major obstacle gives rise to the need to develop efficient network architecture and medium access techniques to overcome this problem.

In this direction we propose a network architecture which suggests several control channels with appropriate multiple access technique in order to overcome the electronic processing bottleneck. The number of control channels and the proper structure of the station interface is related to the speed of interface electronics of a station. In this way a station is able to receive the entire incoming control information as it is distributed amongst all control channels at a lower rate compatible with the feasible electronic speed.

Our proposed architecture and protocol attempts to minimize contention by corresponding for each control channel a data channel. So in the described schemes the control channel collision coincides with data channel collision. In opposite all successfully transmitted control packets guarantee the successful transmission of corresponding data packets reducing the total collisions in the system without feedback information specifying whether there was a collision or not.

The proposed network architecture is suitable for the "tell and go" procedure for the access to data channels, when round trip propagation delays are more longer than the packet transmission times. Also this policy has the advantage of decreasing the waiting time before the data packet transmission compared with protocols in which a station transmits the data packet after determining first the successful transmission of the corresponding control packet. The proposed protocol belongs to the synchronous transmission category.

In the receiving mode, when a station identifies at the end of the control slot its address announced in a control packet on a control channel the corresponding data packet will be transmitted successfully. Then, the station immediately adjusts its tunable receiver to the wavelength channel specified in the control packet for data packet reception.

The effect of receiver collision is not studied in this study.

Our investigation is carried out as follows: Section 2 introduces the proposed Multichannel Control Architecture (MCA) network architecture model and assumptions. Section 3, examines the proposed synchronous transmission protocol. A Markovian Model and Analysis are presented for finite population. In Section 4, numerical results from the analysis are provided and comments on numerical results. Finally some conclusions can be found in section 5.

## 2 Network Architecture Model

The system under consideration as Figure 1 shows is a passive star network. The system uses $2N$ wavelengths, $\lambda_{c1},...,\lambda_{cN},\lambda_{d1},...,\lambda_{dN}$, to serve a finite number $M\,(M > N)$ of stations. The multichannel system at wavelengths $\lambda_{c1},...,\lambda_{cN}$ forms the Multichannel Control Architecture (MCA) and the remaining $N$ channels at wavelengths $\lambda_{d1},...,\lambda_{dN}$ constitute the data multichannel system. There is one to one correspondence among control channels and data channels and for each control channel wavelength $\lambda_{ci}$ exclusively corresponds to a data channel wavelength $\lambda_{di}$. Thus the proposed network model with the MCA is described as $[CC]^N - TT - [FR]^N - [TR]$. It means that there are $N$ control channels and each station has a tunable transmitter tuned at $\lambda_{c1},...,\lambda_{cN},\lambda_{d1},...,\lambda_{dN}$. The outcoming traffic from a station is connected to one input of the passive star coupler.

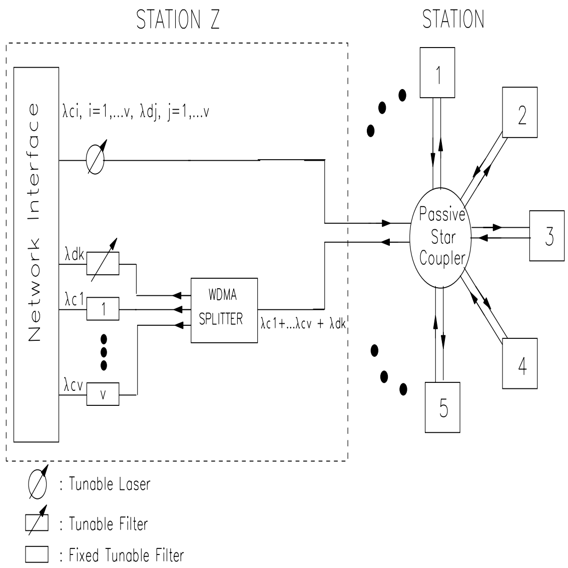


**Figure 1: Passive star architecture and packets structure**.

Every station also uses $N$ fixed tuned receivers one for each control channel and a tunable receiver to any of data channel $\lambda_{d1},...,\lambda_{dN}$. The incoming traffic to a user station is splitted into $N+1$ portions by a $1\times(N+1)$ WDMA splitter as Figure 1 indicates. The transmission time of a fixed size control packet is used as time unit (minislot) and the data packet transmission normalized in minislots time units is $L(L>1)$ which is called data slot. The control packet is consisted of the transmitter address, the receiver address and the wavelength pair $(\lambda_{ci},\lambda_{di})$ as is shown in Figure 1.

Both control channels and data channels use the same time reference which we call cycle. We define as cycle, the time interval that includes one time unit for control packets transmissions followed by a data packet transmission. Thus the cycle time duration is $C = L+1$ time units. Time axis in is divided into contiguous cycles of equal length and stations are synchronized for transmission on the control and data packet transmission during a cycle. All pairs of $(\lambda_{ci},\lambda_{di})$ channels are synchronized in a parallel system of N cycles constituting a multicycle, and the stations are obliged to (re) transmit at the beginning of each multicycle. The access method follows the “tell and go “ policy.

Every station has a retransmission buffer with capacity of one packet. If the retransmison buffer is empty the station is said to be *free*, otherwise its it is *backlogged*.

Packets are generated independently at each station following a geometric distribution, that is, a packet is generated at each cycle with probability σ; if the station is backlogged the packet is lost and never returns. If a transmission is unsuccessful due to collisions the packet enters the station buffer and the station becomes backlogged. Each backlogged station schedule to retransmit during a cycle with probability p.

A station a station generating or retransmitting a data packet, selects randomly one of the $N$ wavelengths pairs $(\lambda_{ci}, \lambda_{di}) \in \{(\lambda_{c1}, \lambda_{d1}),...,(\lambda_{cN}, \lambda_{dN})\}$ and sends first the control packet over the $\lambda_{ci}$ control channel at the first time unit of the cycle. If the control packet transmission is successful, this ensures that the corresponding data packet will be transmitted without collision over $\lambda_{di}$ wavelength data channel in the next time unit.

A station will hear the result of the transmission of its control and data packet because of the broadcast nature of the passive star coupler communication system. In the receiving mode if a station sees its address announced in a control packet, immediately adjust its tunable receiver to the transmission wavelength channel which is specified in the control packet for packet reception. We consider that at any point in time each station is capable of transmitting at a particular wavelength $\lambda_{dT}$ and simultaneously receiving at a wavelength $\lambda_{dR}$. In addition tuning times and propagation delays are assumed negligible.

# 3 Analysis

The behavior and the performance of the examined system can be described by a discrete time Markov chain. We denote the state of the examined system by $B^t, t = 0,1,2,...$ where $B^t$ is the number of busy stations at the beginning of each cycle.

$S^t, t = 0,1,2,...$ where $S^t$ is the number of successful (re)transmissions at the beginning of the slot.

$A^t, t = 0,1,2,...$ where $A^t$ is the number of new packets arrivals at the beginning of the slott.

$H^t, t = 0,1,2,...$ where $H^t$ is the number of new and retransmission packets arrivals at the beginning of the slot.

Let

$S_v =$ The number of successful (re)transmissions during a cycle.

$S_v(k) =$ The number of successful data packet (re)transmissions, conditional that k free and/or backlogged stations attempt transmission during a cycle. $0 \le S_v(k) \le \min(v,k)$ .

The probability $S_v(k) = n$ , of n success from k (re)transmissions during a cycle is given [7,8] by

$$P[S_v(k) = n] = \frac{(-1)^n N!k!}{N^k n!} \sum_{j=n}^{\min(N,k)} \frac{(-1)^j (N-j)^{k-j}}{(j-n)!(N-j)!(k-j)!} \quad (1)$$

with $0 \le n \le \min(v,k)$

It is obvious that the Markov chain $\{B^t, t = 0,1,2,...\}$ is homogenous, aperiodic and irreducible. The one step transition probabilities are given by

$P_{nm} = P(B^{t+1} = m / B^t = n)$ , where

$$P_{nm} = \begin{cases} 0 & m < n-N \\ q_{Nn} Q_{0n} P[S_v(v) = v] & m = n-N \\ \sum_{k=n-m}^{n} q_{kn} \sum_{j=0}^{\min(M-n,m-n+N)} Q_{jn} P[S_v(k+j) = j+n-m] & n-N < m \le n \\ \sum_{k=0}^{n} q_{kn} \sum_{j=m-n}^{\min(M-n,m-n+N)} Q_{jn} P[S_v(k+j) = j+n-m] & m > n \end{cases} \quad (2)$$

$$q_{kn} = \binom{n}{k} r^k (1-r)^{n-k} \quad (3)$$

$$Q_{jn} = \binom{M-n}{j} \sigma^j (1-\sigma)^{M-n-j} \quad (4)$$

### Performance Measures

**Steady state Probabilities**

Since the Markov chain { $B^t, t = 0,1,2,...$ } is ergodic, the steady state probabilities can be found solving the system of linear equations.

$$\pi = \pi P \qquad \sum_{n=0}^{M} \pi_n = 1 \quad (5)$$

where $P$ is the transition matrix with elements the probabilities $P_{nm}$ and $\pi$ is a row vector with elements the steady state probabilities $\pi_n$. We are now in the position to calculate performance measures of the proposed protocol.

**Throughput, $S_T$**

*Conditional Throughput*

$S(i)$, is the expected value of the output rate during a cycle given that the number of backlogged stations at the beginning of the cycle is $i$

$$S(i) = E[S^t / N^t = i] = ip(1-\frac{p}{N})^{v-1}(1-\frac{\sigma}{N})^{M-i}$$
$$+(M-i)\sigma(1-\frac{\sigma}{N})^{M-i-1}(1-\frac{p}{N})^i \quad (6)$$

The steady state average Throughput $S_T$, is given by

$$S_T = \sum_{i=0}^{M} \pi_i S(i) \quad (7)$$

$S_d$ = the average rate of successfully transmitted data packets through one of the data channels per cycle.

$$S_d = \frac{S_T}{N} \quad (8)$$

**Input rate, $S_{in}$**

*Conditional Input Rate*

$S_{in}(i)$, is the expected number of arrivals during a cycle given that the backlogged stations at the beginning of the cycle is $i$.

$$S_{in}(i) = E[A^t / B^t = i] = (M-i)\sigma \quad (9)$$

The steady state average Input rate $S_{in}$, is given by

$$S_{in} = \sum_{i=0}^{M} S_{in}(i)\pi_i = (M-B)\sigma \quad (10)$$

**Traffic, $G$**

*Conditional Traffic*

$G(i)$, is the expected offered load during a cycle given that the number of backlogged stations at the beginning of the cycle is $i$

$$G(i) = E[H^t / B^t = i] = ip + (M-i)\sigma \quad (11)$$

The steady state traffic $G$ is given by:

$$G = \sum_{i=0}^{M} \pi_i G(i) \quad (12)$$

**Baklogged, $B$**

The steady state backlogged stations $B$, is given by:

$$B = \sum_{i=0}^{M} i\pi_i \quad (13)$$

**Delay**

Delay is the average number of cycles that a data packet has to wait until it is successfully transmitted. Delay is easily calculated through the Little’s Formula, that is:

$$D = L + 1 + (L+1)B / S_T \quad (14)$$

## 4 Numerical Results

In this section, numerical examples are presented by employing the analytical results presented above.

Figure 2 illustrates the offered load $G$ per cycle versus the birth probabilities characteristics for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations and retransmission probability $p$ =0.1. It can be seen that different number of stations provides different loads, and $G$ is an increasing function of $M$ .

Figure 3 shows the throughput per data channel $S_d$ versus the birth probabilities characteristics for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations and retransmission probability $p$ =0.1. It is evident that different loads correspond to different throughput performance per data channel. At light loads as $M$ increases the probability of a channel to be used increases. As the load grows the throughput performance improves approaching a maximum value. So, for $M$ =20, $S_d(\max)$=0.366 and corresponds to $\sigma$ =1, for $M$ =30, $S_d(\max)$=0.378 and corresponds to $\sigma$ =1, for $M$ =50, there are two maxima one at $S_d(\max)$=0.372 and corresponds to $\sigma$ =0.1 and another at $S_d(\max)$=0.362 to $\sigma$ =0.3. Finally for $M$ =80, there is only one $S_d(\max)$=0.369 and corresponds to $\sigma$ =0.04, then the throughput decreases until the value 0.29 at $\sigma$ =1.

Figure 4 depicts the average Delay $D$ versus the birth probabilities characteristics for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations, L=100 minislots and retransmission probability $p$ =0.1. We observe that the average delay is increasing function of $M$ . The explanation comes from Figure 2. So as $G$ increases the collision probability on data channels grows that consequently increases $D$ .

Figure 5 illustrates the average Delay $D$ versus the throughput per data channel $S_d$ for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations, L=100 minislots and retransmission probability $p$ =0.1. It can be seen that $D \rightarrow S_d$ curves deteriorate as

$M$ increases and on the other hand the system is not stable, because there are two different values of

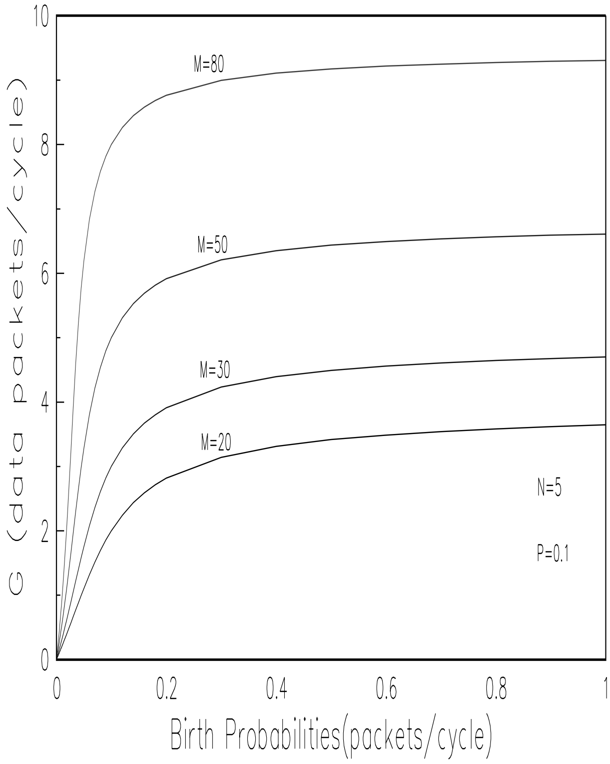


**Figure 2: The offered load $G$ per cycle versus the birth probabilities characteristics for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations and retransmission probability $p$ =0.1.**

delay associated with a given throughput and some dynamic control procedure will be required to stabilize the system.[9,10]. Also the lower part of the curves $D$ increases very slowly with throughput showing the region of the high system performance and low delay.

Figure 6 depicts the comparison of the average Delay $D$ versus the throughput per data channel $S_d$ for a $N$ = 5,10,20,30 (data channel)system, L=100 minislots and $M$ =50 stations with retransmission probability $p$ =0.1. It can be observed that the delay, $D$ , measures are on decrease as $N$ increases for all values of control probabilities $\sigma$ .

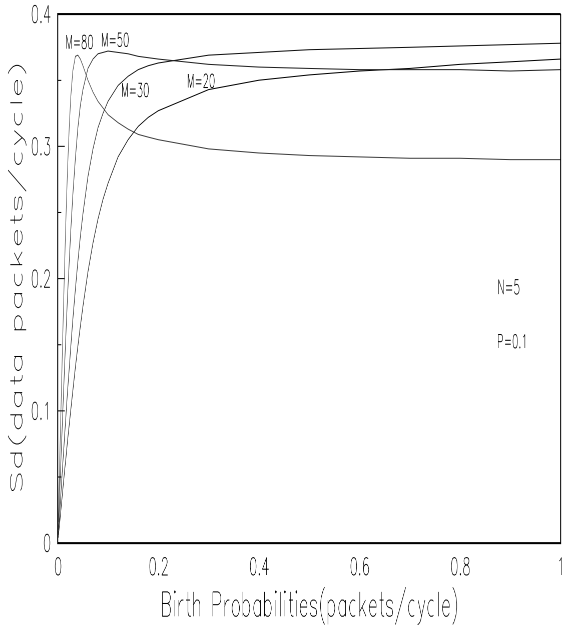


**Figure 3: The throughput per data channel $S_d$ versus the birth probabilities characteristics for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations and retransmission probability $p$ =0.1.**

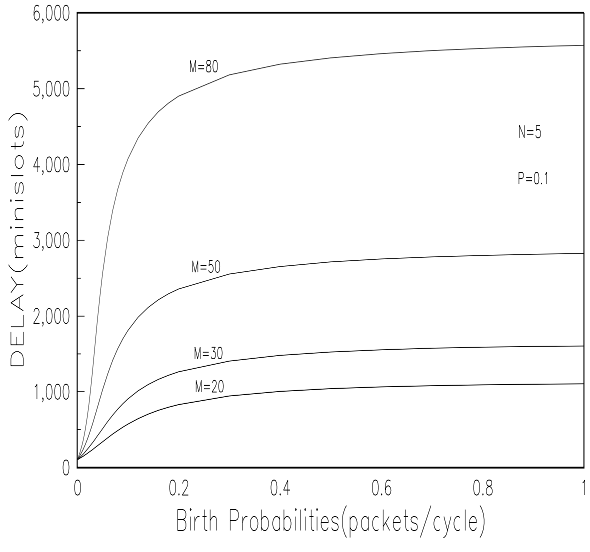


**Figure 4: The average Delay $D$ versus the birth probabilities characteristics for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations, L=100 minislots and retransmission probability $p$ =0.1.**

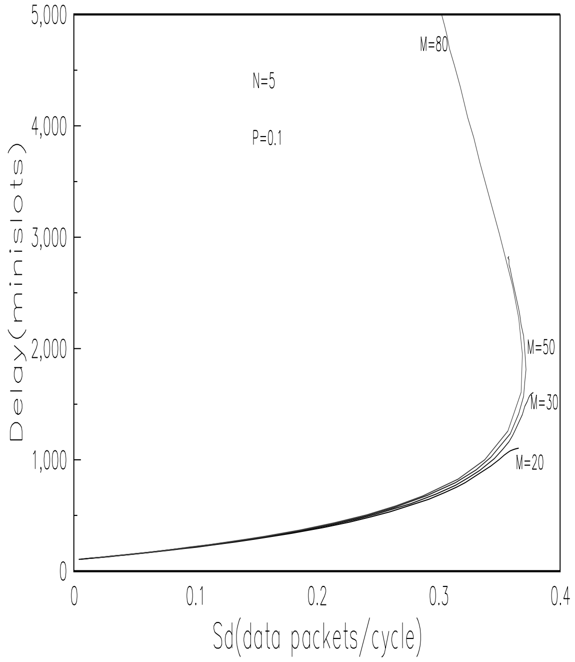


**Figure 5: The average Delay $D$ versus the throughput per data channel $S_d$ for a $N$ =5 (data channel)system with $M$ =20,30,50,80 stations, L=100 minislots and retransmission probability $p$ =0.1.**

# 5 Conclusions

This paper introduces a WDM network architecture and provides a detailed analysis based on a Markovian process describing the backlogged stations at the beginning at each cycle as the state of the system. The main goal of the paper is to overcome the major limitations affecting the WDM networks operation. The novel concept of the Multichannel Control Architecture and the distribution of control information over a number of control channels, in conjunction with the fixed tuned receivers, minimize the headers processing requirement at each station. The proposed Multichannel Control Architecture is a solution to the problem of the electronic processing bottleneck that the single common shared control channel for pretransmission coordination introduces in WDM networks.

In other words, he headers processing requirement is minimized due to multiplicity of fixed tuned receivers at each station. So each station fixed receiver has only to process packet headers at rate divided by a factor N (fixed tuned receiver number). Also the conjunction of a control channel and a data channel guarantee the successful transmission of a data packet when the accompanying control packet is successful. In this way, the proposed network rules out the possibility of data channel collision making more efficient the use of the optical bandwidth by improving the throughput performance of the network. Finally the synchronous transmission protocol nullifies the vulnerable period of data packet reception at destination improving any more performance of the system.

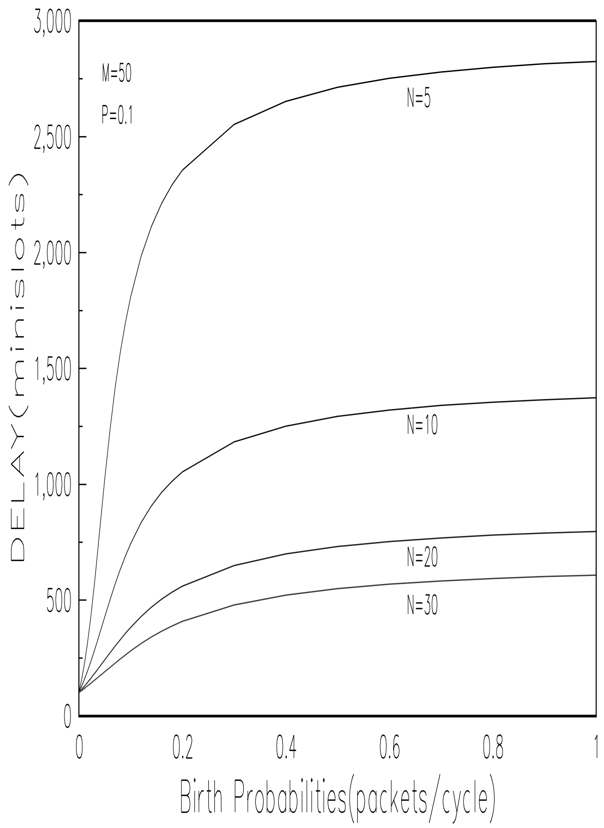


**Figure 6: The average Delay $D$ versus the throughput per data channel $S_d$ for a $N$ = 5,10,20,30 (data channel)system, L=100 minislots and $M$ =50 stations with retransmission probability $p$ =0.1.**

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