The Effects of Power Control on the Optical CDMA Random Access Protocol

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Abstract—In this work, the performance of the hybrid system that combines the distributed power control algorithm (DPCA) with the random access protocol as a novel and simple scheme of achieving a high performance in decentralized optical code division multiple access (OCDMA) networks has been investigated. The multiple access interference (MAI) and the near-far problem effects have been considered. The DPCA advantage lies in its characteristics to be effectively implemented to each node, since only local parameters are necessary. The principal results have shown that the network throughput and delay are strongly affected by the near-far problem and the DPCA works to solve this problem. Hence, the introduction of a certain level of the power control to the random access temporally coded (1D) or the time-wavelength coded (2D) OCDMA networks has demonstrated profitability of the throughput increase and the delay reduction. As a consequence, the proposed system configuration with the DPCA using a very low number of iterations has resulted in a better throughput and simultaneously in a delay decrease when compared to the system without power control mechanisms.

Index Terms—Distributed power control algorithm, random access protocol, optical code division multiple access, 1D-OCDMA, 2D-OCDMA.

I. INTRODUCTION

The continuous increase of traffic in local area networks (LAN) and metropolitan area networks (MAN) has motivated the development of efficient and low-cost technologies to obtain all-optical multi-access networking [1]. The optical code division multiple access (OCDMA) is considered one of the promising methods of optical access [1] [2]. In this kind of access, each node or user is recognized by its code and a different code can share a given common channel. In the common channel, the interference that may arise between different codes is known as the multiple access interference (MAI) and can limit the number of codes utilizing the channel simultaneously [2]. The using of the OCDMA can provide advantages such as asynchronous transmission, soft capacity on demand, high degree of scalability, communication security, non-existence of packet collisions and quality of service (QoS) at the physical layer [1]–[4]. In the OCDMA network, distinct distances between the nodes introduces the near-far problem, thus an efficient power control is needed to overcome this problem and enhance the performance and the throughput of the network [5], [6]. In this case, the distributed power control algorithm (DPCA), analogous to the CDMA cellular system, is one of the most important issues because of its significant impact on both performance and capacity; it is the most effective way to avoid the near-far problem and to increase the capacity [7].

In the OCDMA area, most efforts have been concentrated on the physical layer and there are few contributions to the studies of its network or link layer [8]–[11]. These studies have shown the need to consider the random access protocol that prevents the throughput degradation in the OCDMA networks at low and high offered load [8]. The works in literature have assumed the ideal equal received power from all the nodes to analyze the random access protocols [8]–[11]; however, it is not a real hypothesis because this goal could not be reached easily [5] [6].

In this context, the performance of the hybrid system that combines the DPCA with the random access protocol as a novel and simple scheme of achieving a high performance in the decentralized OCDMA networks has been investigated.

This paper is organized in five section. A review on temporally (1D) and time-wavelength (2D) OCDMA networks is offered in Section II. Section III discusses how random access protocol (ALOHA) is applied to OCDMA network, while Section IV describes centralized and distributed power control procedures in order to improve the throughput and capacity OCDMA network. Numerical results comparing the transmitted power, normalized throughput and delay for both 1D and 2D-OCDMA networks, under power control algorithms and in the absence of these mechanisms are analyzed on Section V. Finally, the main conclusions of this work are offered in Section VI.

II. OCDMA NETWORKS

The OCDMA architecture considered is formed by the \( K \) nodes interconnected by a passive star coupler in a broadcast-and-select pattern. For viability characteristics, it is considered that the network equipment such as code-processing devices (encoders and decoders at the transmitter and the receiver) and the star coupler could be made using robust, lightweight, and low-cost technology platforms with commercial off-the-shelf technologies [12], [13]. The transmitting and receiving nodes create the virtual path based on the code and the total link length is given by:

\[
d_{ij} = d_{ij}^{tx} + d_{ij}^{rx},
\]

where \( d_{ij}^{tx} \) is the link length from the transmitting node to the star coupler and \( d_{ij}^{rx} \) is the link length from the receiving node.
to the star coupler. The received power at a \(j\)-th node is given by
\[
P_{R_j} = a_{\text{Star}} P_i \exp (-a \cdot d_{ij}) ,
\]
where \(P_i\) is the transmitted power by \(i\)-th transmitting node, \(a\) is the fiber attenuation, with the star coupler attenuation, in dB, given by:
\[
e_{\text{Star}}^{\text{dB}} = 10 \left[ \log_{10} K - (\log_2 K) \cdot \log_{10} \delta \right] \quad [\text{dB}]
\]
with \(\delta\) been the excess loss ratio.

A. Temporally Coded (1D) OCDMA

With the aim to work with simple OCDMA system, we choose non-coherent prime codes, namely temporally coded (1D) OCDMA, to develop this study, because this kind of code can be generated simply by using optical passive components, have higher correlation value than conventional optical orthogonal codes (OOC) [14]–[16], and can simultaneously support more number of users than conventional optical orthogonal codes (OOC) [14]–[16]. Furthermore, the ease of generation of prime codes makes them attractive for OCDMA networks [16].

Let \(q\) be a prime number. A prime code of length \(L = q^2\) and weight \(q\) is derived from a set of prime sequences \(S_i = \{s_{i0}, \ldots, s_{ij}, \ldots, s_{i(q-1)}\}\), where \(i \in GF(q)\) - Galois Field, and \(s_{ij} \equiv \{i \cdot j\} \mod q\) [15]. A prime code with \(q\) distinct codewords, \(c_i = \{c_{i0}, c_{i1}, \ldots, c_{ik}, \ldots, c_{i(L-1)}\}\) for \(k = 0, 1, 2, 3, \ldots, L - 1\), are thus constructed by [15]
\[
c_{ik} = \begin{cases} 1, & k \equiv s_{ij} + jq \mod q \quad \text{and} \quad j \in GF(q) \\ 0, & \text{otherwise} \end{cases}
\]

Also, the choice of non-coherent prime codes has been made based on the various optical coding sequence schemes for non-coherent OCDMA communications and networks studied recently, particularly, the prime code (PC) families, including the extended prime code (EPC) and the modified prime codes (MPCs) [17]–[19]. These studies have illustrated the practical, implementable and efficient system with the higher throughput and spectral efficiency when compared to other coherent and non-coherent OCDMA systems [16]. In addition, at the optical receiver side, low-complexity multiuser detection methods, such as successive interference cancelation (SIC) scheme to substantially reduce the MAI and increase system capacity of non-coherent OCDMA, has been studied [20].

B. Time-Wavelength Coded (2D) OCDMA

The 2D codes are a key concept in order to implement the time-wavelength coded (2D) OCDMA networks. They can be represented by \(N_\lambda \times N_T\) matrices, where \(N_\lambda\) is the number of available wavelengths in the entire code family, and \(N_T\) is the code length, which is determined by the bit period \(T_b\) which is subdivided in small units called chips each of duration \(T_c = T_b / N_T\). In each code there are \(w\) short pulses of different wavelength, where \(w\) is the weight of the code. Hence, an \((N_\lambda \times N_T, w, \lambda_a, \lambda_c)\) code is a collection of binary \(N_\lambda \times N_T\) matrices each of code weight \(w\), with \(\lambda_a\) and \(\lambda_c\) representing nonnegative integers constraints on the autocorrelation and crosscorrelation [15].

In this work, our analysis is based on two-dimensional multiple-wavelength optical-orthogonal codes, 2D MWOOCs [16]. These codes are designed such that there is at most one pulse per wavelength and have been constructing based on prime code \((q \times q^2, q, 1, 0)\).

C. Normalized Throughput

We have adopted as method of comparing 1D and 2D OCDMA codes the normalized throughput, \(\beta'\). This metric is utilized to compare optical codes of different families, sizes and weights, been defined as [21]:
\[
\beta' = \frac{\beta}{N_\lambda N_T}
\]
where \(\beta\) is the nominal throughput of the steady state OCDMA network, which in the Slotted-ALOHA (or S-ALOHA) context [11] will be defined more precisely in Section III. Note that an one-dimensional code will have \(N_\lambda = 1\), while under two-dimensional code \(N_\lambda > 1\).

It is worth to note that, in general, the performance of 2D codes is better than schemes that applying 1D codes when the BER is considered as metric; however, in 2D-OCDMA systems there is an expansion of the number of wavelengths (or equivalently the optical bandwidth), as well as an increase on system complexity [16].

III. RANDOM ACCESS OCDMA PROTOCOL

In [8]–[11] different protocols for OCDMA networks have been proposed and analyzed. The S-ALOHA [11] is better protocol when the user’s activity and the offered traffic are high, whereas other one, like round robin receiver/transmitter (R3T) is better for smaller values of user’s activity and moderate traffic [10].

In this work we adopt S-ALOHA aiming to reach a good performance with low complexity [10]. In the S-ALOHA the traffic is distributed according to the user’s activity. Herein, the traffic is modeling by general Markov chain, as illustrated in Fig. 1. In this model, each node can be in one of the three modes at a time: origination mode (O), transmission mode (T), or backlog mode (B) [9]. The user in the origination mode generates and transmits a new packet at the beginning of the next time slot with a probability \(P_o\). The user enters the backlog mode when an attempt to transmit a new packet fails. This event occurs with probability \(1 - P_c\), where \(P_c\) is the correct packet probability of the corresponding system. The retransmissions of a backlogged packet occur in any given time slot with probability \(P_r\). In the backlogged mode, the blocked terminal cannot generate new packets until the backlogged packet is received correctly.

![Fig. 1. Traffic model based on general Markov chain.](image-url)
The success packet probability is related to the bit error probability by \( P_c = [1 - P_b]^N \), where \( N \) is the packet length in bits. Adopting Gaussian approximation, the probability of bit error is given by \( P_b = \text{erfc} \left( \sqrt{\gamma} / 2 \right) \), where \( \gamma \) is the signal-to-noise ratio, SNR.

Assuming \( P_r = P_o \), the arrival distribution can be approximated by either a binomial distribution if the number of users in the system is finite or by a Poisson distribution if it is very high. Let be \( P_e(\ell) \) the conditional packet success probability given that \( \ell \) packets were transmitted in the same time slot. The conditional mean of the number of successful packets \( S \) is given by \( \mathbb{E} \{ S | \ell \} = \ell \cdot P_e(\ell) \). Hence, the steady-state throughput \( \beta \) is the expected number of successful packets per slot given by [9] [11]:

\[
\beta = \sum_{\ell=1}^{\infty} \ell \cdot f_I(\ell) \cdot P_e(\ell)
\]

where \( f_I(\cdot) \) is the probability mass function for the arrival process \( I \). For the arrival distribution approximated by a binomial distribution, the steady-state throughput is given by

\[
\beta = \sum_{\ell=1}^{K} \ell \cdot \left( \frac{\bar{Q}}{K} \right)^{\ell} \left( 1 - \frac{\bar{Q}}{K} \right)^{K-\ell} \cdot P_e(\ell)
\]

where \( \bar{Q} \) is the average offered traffic rate, and \( K \) is the number of nodes or users in the optical network. The average offered traffic is composed of newly generated successfully transmitted packets and successfully retransmitted packets, and it is computed as [8]:

\[
\bar{Q} = (K - \bar{n}) P_o + \bar{n} P_r
\]

where \( \bar{n} \) is the expected channel backlog. The average packet delay is defined by Little’s theorem as the average number of backlogged users over the system throughput as [9]

\[
D = \frac{\bar{n}}{\beta} + 1
\]

IV. POWER CONTROL PROCEDURES FOR OCDMA

In order to achieve a specific quality of service (QoS), which is associated to a maximum bit error rate (BER) tolerated by the \( i \)-th optical node, the carrier to interference plus noise ratio (CINR) at the required decoder input can be defined as:

\[
\Gamma_i = \frac{G_{ii} p_i}{\sum_{j=1,j\neq i}^{K} G_{ij} p_j + \sigma_i^2} \geq \Gamma_i^*
\]

where \( p_i \) is the \( i \)-th node transmitted power, \( \sigma_i^2 \) is the power of receiving noise, \( \Gamma_i^* \) is the established CINR target value, and the elements \( G_{ij} \), that represent the connections of transmitter-receiver pairs, constitute the network attenuation matrix:

\[
G = \begin{bmatrix}
G_{11} & G_{12} & \cdots & G_{1K} \\
G_{21} & G_{22} & \cdots & G_{2K} \\
\vdots & \vdots & \ddots & \vdots \\
G_{K1} & G_{K2} & \cdots & G_{KK}
\end{bmatrix}
\]

where \( G_{ij}, \forall i \neq j \), corresponding the attenuation factor from the interferer user’ signal \( j \) to interest user’ signal, \( i \).

Note that the usual receiver noise power \( \sigma_i^2 \) in (10) includes thermal noise, shot noise and optical preamplifier noise. However, the amplified spontaneous emission (ASE) in the optical preamplifier will be the main limiting factor (in addition to the MAI), compared to thermal and shot noise at the receiver [5]. In this work, the receiver noise power is represented as

\[
\sigma_i^2 = 2 \cdot n_{SP} hf (G - 1) B_o g_p
\]

which take into account the two polarization mode presented in a single mode fiber [22]. \( P_N \) is the spontaneous noise power at the output of the amplifier for each polarization mode, \( n_{SP} \) is the spontaneous emission factor, typically around \( 2 - 5 \), \( h \) is Planck’s constant, \( f \) is the carrier frequency, \( G \) is the amplifier gain and \( B_o \) is the optical bandwidth. Ideally, to reduce the ASE noise power, the optical bandwidth can be set to a minimum of \( B_o = 2R \), where \( R \) is the bit rate.

Incorporating in (10) the spreading bandwidth inherent to OCDMA, we can define the signal to interference plus noise ratio (SNR) at each optical node. As the same manner of CINR, the SNR must be not lower than an established target value \( \gamma_i^* \) associated to a maximum BER tolerated by the \( i \)-th optical node. Hence, considering temporally (1D) prime codes, each node transmitted power, \( p_i \), has to be controlled in order to satisfy [5]:

\[
\gamma_i^{1D} = \frac{\sigma_i^2}{\rho_{1D}}, \Gamma_i \geq \gamma_i^*, \quad i = 1, \ldots, K
\]

where \( \rho_{1D} \) is the prime code mean cross-correlation value.

In case of time-wavelength coded OCDMA networks, it has been shown in [23], [24] that the SINR for 2D-OCDMA system is obtained substituting \( q \) by \( N_T \) in (13), and, in addition, considering the MWOOC mean cross-correlation value, \( \rho_{2D} \) [15], [16]:

\[
\gamma_i^{2D} = \frac{N_T^2}{\rho_{2D}}, \Gamma_i \geq \gamma_i^*, \quad i = 1, \ldots, K
\]

A. Optimizing the Laser Powers

The power control in optical networks is an optimization problem. Defining the \( K \)-dimensional column vector of the transmitted optical power \( p = [p_1, p_2, \ldots, p_K]^T \), then the optical power control problem consists in finding the optical power vector \( p \) that minimizes the cost function [6]:

\[
J(p) = 1^T p = \sum_{i=1}^{K} p_i
\]

subject to the constraints:

\[
\Gamma_i \geq \Gamma^*, \quad P_{\min} \leq p_i \leq P_{\max}, \quad \forall i = 1, \ldots, K
\]

where \( 1^T = [1, \ldots, 1] \) and \( \Gamma^* \) is the minimum CINR to achieve a desired QoS.

Using matrix notations, eq. (10) can be written as:

\[
[1 - \Gamma^* H] p \geq u,
\]
where \( \mathbf{I} \) is an identity matrix, \( \mathbf{H} \) is the normalized interference matrix, whose elements can be evaluated from (11) as:

\[
H_{ij} = \begin{cases} 
0, & i = j, \\
\frac{G_{ij}}{G_{ii}}, & i \neq j,
\end{cases}
\]

and

\[
u_i = \frac{\Gamma^* \sigma_i^2}{G_{ii}},
\]

(18)

Note that in (18) we have a scaled version of the noise power. Solving (16) substituting inequality by equality, we get the optimized power vector solution through matrix inversion:

\[
p^* = [\mathbf{I} - \Gamma^* \mathbf{H}]^{-1} \mathbf{u}
\]

(19)

This optical power vector represents the case of power equilibrium at the receiver node, and is then the optimal power required achieving the target CINR. Increasing the value of the CINR would result in higher optical power values that could result in a maximum power higher than the allowed. In this case possible solutions would be obtained either by fixing or decreasing \( \Gamma_i \) values or even removing (switching off) some users (worst CINR ones) from the network.

The centralized power control is obtained by matrix inversion and corresponds to an existence of a central node. The central node storages information about all physical network architecture like fiber length between nodes and regular update about transmission establishment and dynamic of traffic. These characteristics are the drawback of centralized control. On other hand, the distributed power control algorithm (DPCA) synthesis consists of the development of a systematic procedure for the vector \( p \) evolution in order to reach the optimum value \( p^* = [\mathbf{I} - \Gamma^* \mathbf{H}]^{-1} \mathbf{u} \), based on the \( \gamma_i \), \( \gamma_i^* \) and \( p_i \) values. The optimum solution for the power allocation problem satisfies the following associate iterative process [25]

\[
p_i[n + 1] = p_i[n] - \alpha \left( 1 - \frac{\gamma_i^*}{\gamma_i} \right) p_i[n], \quad i = 1, \ldots, K
\]

(20)

where \( \alpha \) is the convergence factor with guarantee of convergence within the range \( 0 < \alpha < 1 \). This equation represents the DPCA proposed by Foschini and Miljanic for CDMA wireless network [25] and it can be effectively adapted for optical networks.

Note that the convergence factor \( \alpha \) in (20) is the numerical integration step to solve an ordinary differential equation, which with some minor alterations is also considered in many other subsequent studies of power control algorithms [26], [27]. Herein, the algorithm represented by equation (20) was evaluated for positive and no greater than 1 values of \( \alpha \), since it has been shown in [25] that the algorithm diverges outside this interval. This parameter is responsible for the convergence speed; values close to 1 indicate fast convergence, but with some degradation in the final solution, when compared with values close to 0, which results in slow convergence [27].

B. DPCA Implementation in a Distributed Fashion

The DPCA of equation (20) could be implemented in each optical node because all necessary parameters (SINR level given by \( \gamma_i^* \) and the transmitted power \( p_i[n] \)) is known in the node. It is possible to measure \( \gamma_i[p] \) without the effective knowledge of the information from interferer nodes, which in accordance with equation (13) would be necessary. Thus, (20) depends on local parameters just allowing that the power control works in a distributed manner. There are more details about several aspects that we don’t discuss here, such as, convergence, proximity to the optimum value, and sensibility to estimation errors as well, that is discussed in details on [6], [25], [26], [28]. To cope with the SINR optimization the minimum power constraint (which is also called sensitivity level) assures that the optical signal can be detected by all optical devices. The maximum power constraint \( P_{\text{max}} \) guarantees the minimization of nonlinear physical impairments, because it makes the aggregate power on a link to be limited to a maximum value bounded by the laser constructive aspects.

V. Numerical Results

We have considered 31 nodes. So, for the temporally Coded (1D) OCDMA, results \( q = 31 \), while for the time-wavelength coded OCDMA we have adopted the 2D MWOOCs codes with parameters \( (N_1 \times N_T, w, \lambda_1, \lambda_c) \equiv (31 \times 31^2, 31, 1, 0) \). Furthermore, the scenario considered in our study is represented in Fig. 2. The distances between Tx nodes and star coupler are shown in Fig. 2.a, while distances between Rx nodes and star coupler considering the 31 nodes are presented in Fig. 2.b. The nodes are uniformly distributed over an area with a radius between 2 and 50 km; hence, the range of the total link length is \([4; 100]\) Km.

In all numerical results, typical parameter values for the noise power in all optical receivers were assumed [22]. So, in eq. (12), adopting \( n_{SP} = 2 \), \( h = 6.63 \times 10^{-34} \) [JHz], \( f = 193.1 \) [THz], \( G = 20 \) [dB], \( B_o = 30 \) [GHz], immediately we obtain \( \sigma_i^2 = 15 \times 10^{-7} [A^2], i = 1, \ldots, K \).

A. DPCA Convergence and Performance

Fig. 2.c and 2.d present the optimized power assignment per user considering OCDMA system with 1D and 2D codes, respectively. These numerical results for the optimized powers were obtained applying the centralized control strategy, i.e. solving (16) by matrix inversion. The drawback of centralized control is the need of central node with information about the physical network architecture. As one can observe from Fig. 2.c and 2.d, there is a considerable difference between the optimized transmitted powers per user with 1D and 2D codes (\( \approx 9 \) dB). Indeed, in accordance with [13], [16], our numerical results show the higher transmitted power necessary for the 1D-OCDMA system reaches the sensibility of the photodetector at the receive nodes when it is compared with the 2D-OCDMA system. The noise contributions due to the OCDMA en/decoder, as well as the higher MAI impact on the power budget of 1D-OCDMA, has resulted in a substantial difference in the optimal transmitted powers of both systems with parameters considered herein.

Fig. 3 shows the transmitted power per user for the number of iterations with Foschini’ DPCA and \( \alpha = 0.2 \), or \( \alpha = 0.8 \), considering the same scenario presented in Fig. 2. One can see that, for both 1D- and 2D-OCDMA systems, the increasing
B. OCDMA Throughput Performance

With the objective to show the impact of power control on the throughput performance we show at Fig. 4 the normalized throughput for the offered traffic. It was considered the packet length of 500 bits for the same OCDMA network utilized in Fig. 2. It was considered two scenarios, one without power control and other with DPCA ($\alpha = 0.2$) power control for 140 iterations to grant the algorithm convergence for one dimensional (1D) and two-dimensional (2D) codes. For the scenario without power control, the transmitted power for each node was evaluated by static power budget, i.e. without effects of MAI or considerations about number of active nodes.

We can observe from Fig. 4 the impact of power control on the throughput performance. The utilization of DPCA approximates the throughput value presented here with the throughput considering the ideal system, i.e. without different distance for the nodes. In fact, without DPCA the SINR declines, for both 1D and 2D codes OCDMA systems, the packets are more vulnerable to distortion, which reduces the likelihood of their successful transmission and reception. Thus, the probabilities of correct packets collapse, and hence, the throughput decreases.

Furthermore, one can put in perspective the 1D and 2D codes under consideration. In Fig. 4, the 1D code with power control almost present the same performance of 2D code without power control, however at high offered loads, the 1D code with power control outperforms the 2D code without power control. Finally, considering only the case with power control for 1D and 2D code or ideal system, we observe that the peak of normalized throughput of 2D code outperforms the 1D code by a factor of $\approx 1.5$, which is in accordance with the study presented in [21].

![Fig. 2. a) Distance between Tx nodes and star coupler; b) Distance between Rx nodes and star coupler. Optimized power assignment per user for centralized power control approach, considering: c) 1D codes; d) 2D codes.](image)

![Fig. 3. Optimized power assignment per user versus the number of iterations for distributed power control approach, considering $q = 31$ nodes and convergence factor $\alpha = 0.2$ (left) or $\alpha = 0.8$ (right): a) 1D codes; b) 2D codes.](image)
depends on the code parameters [8]–[11]. It can be noticed in other works and it can be shown that this value throughputs reaches its saturation value. This general trend can throughputs and the average packet delay increase until the channel, one can observe the same tendency of the increasing performance of the hybrid system that combines a distributed power control procedure on the global system performance. The adopted iterative algorithm of the DPCA achieves total convergence (28 and 10 iterations for the 1D and 2D codes, respectively). Hence, with few numbers of iteration, the Delay-Throughput curves are near to the optimum one.

VI. CONCLUSIONS

In this work, it has been proposed and analyzed the performance of the hybrid system that combines a distributed power control algorithm (DPCA) with the random access protocol as a simple and effective scheme of achieving a high performance in the decentralized optical code division multiple access (OCDMA) networks. The throughput and the delay of the network are strongly affected by the near-far problem, and the DPCA works to solve this problem in the context of the 1D- and the 2D-OCDMA systems. The DPCA advantage lies in its characteristics to be effectively implemented in each node, since only local parameters are necessary. The numerical results have shown that the optimized transmitted power determined by the DPCA has converged to the optimized transmitted power calculated by the centralized power control, which demands more resource to be implemented.

Furthermore, it has been observed that the OCDMA system with the 1D codes and the power control mechanism presents almost the same performance of the 2D-OCDMA without the power control. However, at the high offered loads, the 1D-OCDMA system with the power control outperforms the 2D-OCDMA in the absence of the power control mechanisms.

Finally, for both the 1D- and the 2D-OCDMA systems, it is worth to notify that under a very low number of iterations (20% and 7% of the iterations for the total convergence, respectively), the proposed DPCA results simultaneously in the better throughput and the delay reduction regarding the OCDMA system without the DPCA. Under this low number
of iterations, both optical systems equipped with the proposed DPCA have been capable to achieve the throughput and the delays very close to the optimum values.

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REFERENCES


