Converged Medium Access Control and Dynamic Bandwidth Allocation for Radio-Over-Fiber Networks

KSHITIZA SINGH, ABHISHEK DIXIT, AND VIRANDER KUMAR JAIN

Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India

Corresponding author: Kshitiza Singh (kshitiza.singh@ee.iitd.ac.in)

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ABSTRACT

For supporting the upcoming applications, wireless mobile users require high bandwidth. To serve these requirements, a wireless network that has an optical backbone with a colossal bandwidth capacity is required. The radio-over-fiber (RoF) network is a promising solution that can provide high bandwidth. To accomplish this goal, we propose a converged medium access control (MAC) protocol for the RoF network, which uses a single-gate or multi-gate polling algorithm for time and wavelength allocation to the users. We propose an analytical delay model for single and multiple wavelength architectures, considering the user identification and data transfer delay for single-gate and multi-gate polling algorithms. We verify it with the results obtained from simulations. Finally, we present the mean delay and packet loss rate of the proposed algorithm by varying the user load and traffic burstiness and prove that the proposed algorithm gives better delay performance and a lower packet loss than the state-of-the-art algorithms.

INDEX TERMS

Dynamic bandwidth allocation, fiber wireless network, medium access control protocol, radio-over-fiber.

I. INTRODUCTION

The development of any nation is impossible without a digital infrastructure as billions of users desire continuous Internet connectivity. People depend on digital services for their basic day-to-day necessities like health-care, education, commerce, entertainment, etc. In the present scenario, digital services are not only an additive aspect of any business, but it has also become indispensable, and this dependency is likely to intensify in the years to come.

In the digital ecosystem, continuous user connectivity is of prime concern. To cater to such demands for billions of users, we require an ultra-high wireless capacity while keeping the mobility intact. The design of the network should focus on providing high bandwidth and mobility to the users. The state-of-the-art networks cannot handle these requirements as the fixed optical networks can provide very high bandwidth with restricted user mobility. Wireless networks ensure user mobility, but the spectrum available is not at par with the bandwidth requirements. Hence, the most promising solution for this is a hybrid optical wireless network having the optical fiber backbone and the wireless link in the last mile.

The primary hybrid optical wireless network is the radio-over-fiber (RoF) network. Moreover, the RoF networks have gained a great deal of attention as access networks in 5G networks and beyond [1], [2]. As shown in Fig. 1, the RoF network comprises a central office (CO) and the remote antenna units (RAUs) [3]. In the RoF network, the CO is responsible for all the signal processing. The data first modulates the RF...
carrier and then the optical carrier [4]. The optical signal is transmitted over the fiber to RAUs. The RAUs receive the optical signal, convert it into an electrical RF signal, and broadcast it to the mobile users present in their coverage area (cell). We keep the design of the RAU simple to minimize the network cost.

The medium access control (MAC) is an essential aspect of the RoF network. It regulates the access of transmission media to avoid a collision when multiple users send the data simultaneously. The critical aspects to consider while designing the MAC protocols are delay and packet loss rate. The mean packet delay needs to be minimized with low packet loss to serve the real-time applications and ensure a high quality of service (QoS) to the users. In this section, we discuss the related work and then we present the contributions of this paper.

A. STATE-OF-THE-ART

RoF is a promising option for access networks. Various architectures have already been proposed in the area of RoF. There are mainly two categories of the RoF architectures, analog RoF (A-RoF) and digital RoF (D-RoF), based on the type of transmitting signal. In the A-RoF architecture, the CO directly modulates the RF signals onto an optical carrier keeping their spectral bandwidth unchanged [5]–[8]. This leads to a higher bandwidth efficiency compared to a D-RoF transmission. Further, D-RoF architecture is also a promising technology for data transmission as it performs better when there are constraints of higher noise figure and non-linearity [9]–[11]. In D-RoF, the RF signal is digitized before being modulated onto an optical carrier. Further, the RoF network architecture can support single and multiple wavelengths to serve the users, and we explain this in detail in Section 2.

In the RoF networks, not much research work have been carried out on MAC protocols. An RoF network can use non-converged and converged approaches of MAC. In the non-converged approach, the CO allocates the resources to the users separately for the optical and wireless parts of the network. In literature, to design the non-converged MAC, the commonly used approach is the interleaved polling with adaptive cycle time (IPACT) [12] algorithm for the resource allocation in the optical part. The IPACT algorithm is a DBA algorithm that uses time division multiple access (TDMA) for the resource allocation to RAUs. In the wireless part of the network, several authors [13]–[15] have suggested carrier sense multiple access with collision avoidance (CSMA/CA) based protocol for resource allocation among the users. The main hurdle in this approach is the surplus delay introduced by the optical fiber, which degrades the network performance.

In converged MAC, the CO is responsible for all the resource arbitration through both optical and wireless parts of the network and supports multiple RAUs and the users [16], [17]. As the CO has a complete view of the network, it can fairly allocate the resources among the users, leading to better performance compared to the non-converged MAC. The protocols, like medium transparent (MT) MAC protocol [18] and MAC for wireless sensors network (WSN) over RoF [19], have been proposed in which the CO distributes the resources directly to the users. The main problems with the proposed protocols are fixed-size data frames. Further, the current resource requirements of the users are not considered, and hence the channel is not utilized efficiently leading to a higher delay.

To overcome these issues, a MAC protocol is proposed in [20], which follows the gated approach for grant-sizing to improve the network performance. Further, in [3], a comparison between non-converged and converged MAC protocols is presented. Here, a MAC protocol for the converged approach is proposed. It is reported that the converged approach performs better than the non-converged approach in terms of mean packet delay and channel utilization. Another MAC protocol for the RoF networks takes into account a hybrid approach [21]. In this, the mobile interleaved polling (MIP) algorithm is proposed, which minimizes the delay compared to the simple polling algorithms, especially for the large cell areas.

The TDMA based DBA algorithms proposed for the RoF networks until now use only single-gate polling in which any new session between the CO and a user could be initiated only after completing the previous one. Here, a user sends the data to the CO after the reception of the GATE message. The CO then sends the next GATE to that user only after the reception of data, followed by the REPORT message, which reports the user’s bandwidth requirement in the next cycle. The main problem with the single-gate algorithms is void formation. A void is a duration in which none of the users is utilizing the uplink channel. To overcome this issue, the authors in [22] propose multi-gate polling in which the CO sends the GATE message to the user even before receiving the REPORT message from the previous GATE, consequently decreasing the void formation. Further, the MAC protocols proposed in the literature for the RoF network for multiple wavelength architecture do not consider the overhead of the time that RAUs require to tune their transceivers following the allocated wavelength.

B. CONTRIBUTIONS

In this paper, we propose a MAC protocol for the RoF networks. The novel contributions of the paper vis-à-vis the related work reported in the previous sub-section are as follows:

1) We propose a converged MAC protocol for the RoF network for single and multiple wavelength architectures suitable for both A-RoF and D-RoF access networks.
2) The proposed MAC considers TDMA based DBA algorithms that use the single-gate and multi-gate polling algorithm for time frame allocation to the mobile users.
3) For the wavelength allocation to the users in multiple wavelength scenarios, we propose dynamic wavelength allocation (DWA) and adaptive DWA (ADWA) algorithms, which allocate wavelength to the RAUs.
4) We propose an analytical model to verify the mean delay obtained through simulations for single and multiple wavelength architectures, considering the delay in identifying the users, handovers, and data transfer for Poisson traffic.
5) We analyze the performance of the proposed MAC for Poisson traffic and verify the results obtained from the proposed analytical model with the simulations.
6) After validating the proposed algorithms for Poisson traffic, we present the simulation results for self-similar traffic for different levels of burstiness.

Finally, we show that the multi-gate polling algorithm reduces the mean packet delay compared to the single-gate polling algorithm within the range of 1 ms up to the practical normalized load of 0.6 for both single and multiple wavelength network architectures (using DWA), which is crucial for 5G systems. We further show that with the use of the multiple wavelength architectures, the network capacity increases. Further, when multi-gate polling is employed in the multi-wavelength architecture, more users can be accommodated in the network with only a slight increase in the mean delay as compared to the single wavelength architecture. Further, using the ADWA algorithm for wavelength allocation, we are able to achieve the similar performance even for highly bursty traffic by optimizing the wavelength allocation cycle length according to the users’ traffic demands.

The paper is organized as follows. Section 2 explains the basic RoF network architecture. Section 3 describes the MAC protocol for an RoF network. Section 4 discusses the dynamic bandwidth allocation. Section 5 evaluates the performance of the proposed algorithms, and finally, Section 6 concludes the work.

II. NETWORK ARCHITECTURE

In this section, we discuss the basic architecture of the A-RoF and D-RoF network. RoF is a promising technology, and can be used in access networks and fronthaul networks, as discussed in [23]. The basic architecture of RoF is proposed in [2]. However, some advanced architectures of RoF are proposed in [21]–[24]. This section explains single and multiple wavelength architectures of the A-RoF and D-RoF network, similar to the architectures proposed in [21]. Further, we consider the cell structure for both types of RoF networks, as shown in Fig. 2, where the cells are deployed in a row-column configuration. Each cell area is $D_c \times D_c$ square unit, and RAUs are deployed at the center of each cell. The RAUs receive the optical signal from the CO and convert it to the RF signal to transmit it to the mobile users residing in their cell.

A. SINGLE WAVELENGTH RoF NETWORK ARCHITECTURE

In single wavelength architecture, at the CO the digital data modulates the RF subcarriers ($f_{r1}, f_{r2}, \ldots, f_{rm}$) corresponding to various RAUs, as shown in Fig. 3. Then the RF signals modulate an optical carrier at $\lambda_o$. We consider a wavelength pair ($\lambda_o, \lambda'_o$) which is shared by all RAUs for the transmission of information where $\lambda_o$ is for the downstream traffic, i.e., for the transmission from the CO to the RAUs, and $\lambda'_o$ for the upstream traffic, i.e., for the transmission from the RAUs to the CO. The optical switch is used to switch the data to the desired RAU. The RAU converts the received optical signal to an electrical signal. The detected electrical signal, which is the same as the modulating RF-band subcarrier signal, is digital to analog converted (DAC) to generate the desired downstream RF signal in the D-RoF. In A-RoF, the DAC is not required as the optical to electrical conversion directly generates the analog RF signal. The RAU then transmits the analog RF signal to the users present in its cell.

B. MULTIPLE WAVELENGTH RoF NETWORK ARCHITECTURE

In a multiple wavelength architecture, the data of the users is steered to the desired modulator, and it modulates the assigned RF subcarrier ($f_{r1}, f_{r2}, \ldots, f_{rm}$). For this purpose,
we use RF pulse generators for D-RoF and analog RF modulators for A-RoF as shown in Fig. 4. Then the RF signals modulate the optical carriers \((\lambda_1, \lambda_2, \ldots, \lambda_n)\). The CO allocates the wavelength pairs \((\lambda_1, \lambda'_1), \ldots, (\lambda_n, \lambda'_n)\), to the RAUs where \(\lambda\) is for the downstream traffic and \(\lambda'\) for the upstream traffic. The CO dynamically assigns the wavelengths to the RAUs, and they have a tunable transmitter and receiver to tune as per the assigned wavelength. The RAUs tune their transmitters and receivers according to the control signal received at \((\lambda_c, \lambda'_c)\) wavelength pair from the CO. Finally, the RAU receives the optical signal and converts it to an electrical RF signal. In A-RoF, the analog RF signal is directly transmitted to the users residing in its cell. However, in D-RoF, the electrical signal generated is digital and needs to be converted to an analog RF signal before transmitting it to the users.

The multiple wavelength RoF architecture provides dynamic wavelength allocation to the RAUs according to the users’ traffic in its cell. Further, we propose the MAC protocols for single and multiple wavelength architectures that use TDMA based resource allocation algorithms, hence it can be used by both A-RoF and D-RoF [2]. We explain the proposed MAC in detail in the next section.

III. MEDIUM ACCESS CONTROL

The shared media networks require a discipline in which the users access the communication channel to avoid a collision that results in the loss of information. The MAC protocol regulates how the users access the communication media. In this section, we describe the proposed MAC protocol for the RoF networks.

The proposed MAC protocol for RoF networks involves registering users present in the network, identifying users, and allocating data frames. As the users are mobile and can move from one cell to another over time, the MAC protocol should facilitate seamless handover to ensure good QoS.

A. REGISTRATION PHASE

This phase starts with the transmission of a short beacon pulse in the control channel by the CO, to all the RAUs, which further broadcast it to all the users in their cell. The users acknowledge their presence in the RAUs to the CO. As the acknowledgment sent by the users is also a very short pulse and indicates only the presence of a user, its collision does not impact the performance of network.

We consider that the users are mobile in the network, so the registration phase repeats periodically after every \(t_g\) time duration to gather information about the current location of the users. The time duration \(t_g\) depends on the type of handovers considered in the network, cell size, and the users’ speed.

The handovers process involves transferring a communication session when a mobile user moves to a neighboring cell. The time required for handovers depends on the cell size and the speed at which the user moves. We explain the process of handover in detail later in this section. We take the maximum communication range of each antenna as \(\sqrt{2}D_c\) considering the scenario when the user moves from a cell to any other diagonal cell. Then, the maximum time to repeat the registration phase, i.e., the registration phase length before the connection drops, is given as

\[
t_{rg} = \frac{\sqrt{2}D_c}{v}\gamma
\]

where \(v\) is the maximum speed at which the user moves and \(\gamma \leq 1\). When \(\gamma\) becomes 1, \(t_{rg}\) is maximum after which the connection drops. The list of some important symbols used in the paper is given in Table 1.

B. IDENTIFICATION PHASE

In this phase, the CO identifies registered users by transmitting a POLL message to the users. The users respond to the CO with a REPLY message that comprises the user’s ID and current location. After successfully identifying the user, the CO replies with an ACK message. To avoid the collision of REPLY messages by the users, we use an approach similar to slotted ALOHA [25]. The user randomly chooses a slot for the transmission of the REPLY message after receiving the POLL. If another user chooses the same slot, then a collision occurs. In that case, the user again senses the medium and chooses another slot to send the REPLY message if the channel is free. The slot size is the sum of the guard time and the time required to send the REPLY and ACK messages. The time required for the identification phase is as given below.

\[
T_{ID} = \Delta_{max} + T_{POLL} + s \times (T_g + T_r + T_{ACK})
\]

where \(\Delta_{max}\) is the maximum round trip time (RTT) and \(s\) is the number of slots in the identification frame. \(T_{POLL}\), \(T_r\), and \(T_{ACK}\) are the time required to send POLL, REPLY, and ACK message, respectively. \(T_g\) is the guard time between successive users.

C. DATA FRAMES

After identifying the users present in the network, a DBA algorithm for wavelength and time frame allocation is required to transfer the data by the users to the CO so that the channel is utilized most efficiently and according to the users’ traffic requirements. For wavelength allocation, we propose fixed and dynamic wavelength allocation algorithms. We also...
TABLE 1. List of Important Symbols and Their Descriptions.

| Symbol | Description |
|--------|-------------|
| \( u \) | Total number of users in the network |
| \( u_\lambda \) | The average number of users per wavelength |
| \( N_\lambda \) | The number of wavelengths in the network |
| \( N_{RA} \) | The number of RAUs in the network |
| \( u_{RA}(i) \) | The number of users in the cell of \( i^{th} \) RAU |
| \( n_{RA}(i) \) | The number of RAUs that changed their wavelength to \( i^{th} \) wavelength |
| \( c \) | Total number of slots for control and signaling |
| \( h \) | The number of slots for control and signaling reserved for handovers |
| \( s \) | Number of slots in identification frame |
| \( N_g \) | The number of GATE messages to be sent to every user in a data transfer cycle in multi-gate polling |
| \( \lambda_n, \lambda_{ho} \) | The arrival rates of existing users and the users after handover, respectively |
| \( \mu_n, \mu_{ho} \) | The service rate of session completion and session handover, respectively |
| \( t_{rg} \) | Length of the registration phase |
| \( T_{ID} \) | Length of the identification phase |
| \( T_g \) | Guard time between two consecutive users |
| \( T_r \) | Time to send the report or REPLY message |
| \( T_{ACK} \) | Time to send the ACK message |
| \( \Delta_{max} \) | Maximum RTT between the CO and a user |
| \( t_w \) | Time after which the wavelength allocation repeats |
| \( T_s \) | The time required by an RAU to tune its transceivers to another wavelength |
| \( T_{cycle} \) | The length of data transfer cycle |
| \( d_{SG}, d_{MG} \) | The delay in the transfer of data packets for single-gate polling and multi-gate polling, respectively |
| \( d_{ho} \) | Handover delay |
| \( d_T \) | Overall mean delay |
| \( d_{\lambda-tx}, d_{\lambda-rx} \) | The data transfer delay with and without the wavelength allocation, respectively |
| \( P_{CD} \) | Probability of connection drop |
| \( \rho_{on} \) | The probability of a user to be in the on-period for self-similar traffic |
| \( \rho_{\lambda} \) | The probability of wavelength switching in ADWA algorithm |
| \( \rho \) | Normalized network load |
| \( \rho_{on} \) | The instantaneous load on a wavelength |
| \( \delta \) | The relative change in the load on a wavelength for self-similar traffic |
| \( L_\lambda \) | Data rate per wavelength |
| \( R \) | Data rate per user |

We use the multi-gate and single-gate polling algorithms for time frame allocation in single and multiple wavelength architectures. These are explained in detail in the next section.

We summarize the proposed MAC protocol, as shown in Fig. 5. The CO periodically updates the users registered in the cell of every RAU after every \( t_{rg} \) time and register the new users according to the registration phase explained above. Then, the CO identifies the users and gathers their traffic demands for resource allocation. For resource allocation in multiple wavelength architecture, the CO first allocates the wavelengths to RAUs and then the time frames to the users. For the transfer of data packets, we use single-gate or multi-gate polling. The wavelength allocation repeats after \( t_w \) time for the even distribution of load on all wavelengths. Note that, \( t_w \) time depends on the type of wavelength allocation algorithm, explained in detail in the next section. The single wavelength architecture, however, has only one wavelength, and all the RAUs are tuned to that wavelength, so there is no wavelength allocation, and the CO directly distributes the time frames to the users.

D. HANDOVERS

In the RoF network, the users are mobile and move from one cell to another, for which the handovers are required. We consider that a cell can maintain \( c \) number of slots for control and signaling, out of which \( h \) slots are reserved for handovers. Let \( \lambda_n \) and \( \lambda_{ho} \) are the arrival rates of existing users and the users after handover, respectively. Besides, we consider the inter-arrival time to be exponentially distributed. The effective incoming traffic is \((\lambda_n + \lambda_{ho})\). Let us assume that the service rate of session completion and session handover is \( \mu_n \) and \( \mu_{ho} \), respectively, then the effective service rate \( \mu \) is \((\mu_n + \mu_{ho})\). We calculate the probability of connection drop by modeling it as a Markov chain, in which we have \( \{0, 1, \ldots, c\} \) states, out of which at a time instant \( c \) sessions can run in a cell.

The connection drops when the user is in \( c \) state of the Markov chain. So, the probability of connection drop is \( P(c) \). Moreover, we use the method proposed in [26] to calculate the probability of connection drop as follows:

\[
P_{CD} = \frac{(\rho_{on})^h}{c!} \times \rho^{(c-h)} \rho_{on}
\] (3)
where $\rho$ is $(\lambda_h + \lambda_{ho})/\mu$, $\rho_h$ is $\lambda_{ho}/\mu$, and $P_o$ is given below.

$$P_o = \left( \sum_{j=0}^{c-h-1} \frac{\rho^j}{j!} + \sum_{j=(c-h)}^{c} \frac{(\rho_h)^j}{j!} \times \rho^{(c-h)} \right)^{-1} \tag{4}$$

In connection drop, the user tries to re-register in the next registration and identification phase to transmit the data packets to the CO.

### IV. DYNAMIC BANDWIDTH ALLOCATION

For even bandwidth allocation among users, a DBA algorithm is required. Another aspect of concern while designing a DBA algorithm is to minimize the mean packet delay. For this, we propose a DBA algorithm for wavelengths and time frames allocation to the users.

#### A. TIME FRAME ALLOCATION

The time frames are allocated to the users based on the multi-gate polling algorithm for the RoF networks based on the adaptive multi-gate polling with void filling (AMGAV) algorithm [22]. In addition, we explain a single-gate polling algorithm and the problems related to it. Then, we give a multi-gate polling algorithm for the RoF networks.

1) SINGLE-GATE POLLING

In a single-gate polling algorithm, a new session is initiated from the CO by sending a GATE message to the users after completing the previous one. After gathering the information about the users and their traffic requirements, the CO maintains a polling table with information about the current traffic requirements of the registered users. The CO polls every user, which share the same wavelength, in a round-robin fashion, for the data transfer, as shown in Fig. 6a. The users send the data packets immediately after receiving the GATE message from the CO. We follow an approach similar to MIP [21] for the data transfer, and the cycle length is approximately calculated as given below.

$$T_{cycle} \approx \max \left\{ \frac{u \times (2T_r + T_g)}{1 - \rho}, \frac{u \times (\Delta_{max} + 2T_r + T_g)}{u - \rho} \right\} \tag{5}$$

where $\Delta_{max}$ is the maximum RTT, and $u$ is the number of users. As the users are mobile, RTT is a variable parameter. Hence, we take maximum drift in RTT, which depends on the user’s speed, as an additional buffer in the guard band. In Eq. (5), when the load is high, the first part of the equation influences the cycle length, whereas in low load, we calculate the cycle length using the second part of the equation.

The main problem with single-gate polling is the void formation, which is the network’s unused bandwidth. Any new session to a user is initiated only after completing the previous one, leading to voids. This problem becomes severe when the maximum RTT of the system becomes large. To mitigate this problem, we use multi-gate polling.

2) MULTI-GATE POLLING

In a multi-gate DBA algorithm based on AMGAV [22], many sessions are initiated between the CO and a user within a cycle, as shown in Fig. 6b. We first compute the number of GATE messages sent to the users within a cycle depending on the current network load. The number of GATE messages also influence the cycle length. The CO maintains a request table in which the request pointer ($R_p$) is created corresponding to every user, which has the information about their current traffic requirements (in bits). Based on this, the CO grants the bandwidth to the users. The CO computes the approximate cycle length at the beginning of each cycle, as given below.

$$T_{cycle} \approx \max \left\{ \frac{u \times N_g \times (2T_r + T_g)}{1 - \rho}, \frac{\Delta_{max} + N_g \times u \times T_g}{\Delta_{max}} \right\} \tag{6}$$

where $N_g$ is the number of GATE messages to be sent to every user. We compute the number of GATE messages to be sent to a user at the beginning of a cycle based on the maximum RTT and bandwidth requirement by all the users as follows [22]:

$$N_g = \min \left( \frac{\Delta_{max} \times L_d}{\sum_{n=1}^{N_g} R_p(n)} \right) \tag{7}$$

where $L_d$ is the data rate and $R_p(n)$ is the request pointer of $n^{th}$ user (in bits). The request table is updated whenever a GATE is issued to a user; the request pointer corresponding to that user is decremented by the grant issued to the user. The CO issues grants to the users based on their request pointer. There would be $N_g$ sub-cycles in $n^{th}$ cycle. To avoid bandwidth monopolization by one user with a high traffic demand, we set a maximum limit ($L_m$) to the number of bytes that the CO can grant to a user. In a sub-cycle, the CO computes the voids as
follows:
\[
\tau_{\text{void}} = \min \left( \frac{T_{\text{cycle}}}{N_g} - u \times (T_g + T_r) - \frac{\sum_{n=1}^{u} R_p(n)}{L_{\lambda}} \right) \tag{8}
\]

Then, the CO over-grants the users to fill the voids by equally dividing the packets that can be adjusted in voids, among all the users, in addition to the packets requested by them.

In a sub-cycle, if the bytes requested by the users need transmission time more than the sub-cycle length, then the CO first grants a gated window to the users that request less than or equal to \(L_{w}\) bytes. The CO accumulates the remaining bytes from \(L_{w}\) bytes for these users, and distributes the accumulated bytes to increase the maximum transmission window available for the remaining users, which are then granted using the limited approach.

After the GATE message is received, the REPORT message is sent by the user, followed by the data packets granted to the user. The CO updates the request table based on the REPORT message that gives information about the newly arrived packets in the queue of the user. The CO adds the newly arrived packets to the request pointer of that user. We observe significant less void formation with this polling algorithm, and consequently, we get better channel utilization.

B. WAVELENGTH ALLOCATION

We use single and multiple wavelength architectures to serve the RoF network users, as explained in Section 2. The single wavelength architecture has only one wavelength, \(\lambda_o\), and every RAU is tuned to that wavelength, as shown in Fig. 7a. The users residing in the cell of the RAUs access the wavelength, \(\lambda_o\), on a time-sharing basis. The data frames are allocated to the users to transmit data packets using a single-gate or multi-gate polling algorithm.

In multiple wavelength architecture, the CO allocates the wavelengths to RAUs as per the total traffic generated by the users in the cells of RAUs, as shown in Fig. 7b. Then, the CO distributes data-frames to the users residing in the cell of RAUs, which are assigned the same wavelength, on a time-sharing basis. The wavelength allocation algorithm is repeated after every \(t_{w}\) time, which is the wavelength allocation cycle, to ensure resource allocation to the users as per their traffic requirements. This subsection proposes dynamic wavelength allocation (DWA) and adaptive DWA (ADWA) algorithms for the wavelength allocation, based on the wavelength allocation cycle time.

1) DWA ALGORITHM

In the DWA algorithm, for the allocation of wavelengths to the RAUs, the CO computes the total number of packets requested by the users in the RAUs as given below.

\[
R(i) = \sum_{j=1}^{u_R(i)} R_u(j) \tag{9}
\]

where \(R(i)\) is the total number of packets requested by the users residing in the cell of \(i^{th}\) RAU, \(u_R(i)\) is the total number of users in the cell of \(i^{th}\) RAU and \(R_u(j)\) is the number of packets requested by the \(j^{th}\) user. Further, to equally distribute the load on all wavelengths, the CO calculates the fraction of the total number of wavelengths required to serve the packets requested by an RAU, as follows:

\[
F_{\lambda}(i) = N_{\lambda} \times \frac{R(i)}{\sum_{i=1}^{N_{\lambda}} R(i)} \tag{10}
\]
where $F_\lambda(i)$ is the fraction of the total number of wavelengths required to serve $i^{th}$ RAU, $N_R$ is the total number of RAUs in the network, and $N_\lambda$ is the total number of wavelengths. The CO sorts the RAUs based on their traffic demands in the ascending order and assigns the wavelengths in that manner. Further, the CO allocates a wavelength to $i^{th}$ RAU, if $F_\lambda(i)$ is less than the residual capacity of that wavelength. Otherwise, the CO checks the same condition for the next wavelength till a wavelength is assigned to the RAU. After the wavelength assignment, the CO updates the residual capacity of that wavelength. This process is repeated till the CO allocates wavelengths to all the RAUs. However, if no wavelength can serve the traffic demands, then the wavelength with the maximum residual capacity is assigned to that. Further, we consider that the network suffers from an additional delay because of the penalty incurred in the tuning of the RAUs from one wavelength to another. Therefore, the next data transfer cycle length for single-gate polling for $i^{th}$ wavelength is calculated as follows:

$$T_{cycle} = \max \left\{ \frac{u_k(i) \times (2T_r + T_g)_i + n_R(i) \times T_i}{1 - \rho}, \frac{u_k(i) \times (\Delta_{max} + 2T_r + T_g) + n_R(i) \times T_i}{u_k(i) - \rho} \right\}$$  

(11)

where $u_k(i)$ is the average number of users in the cells of RAUs tuned to $i^{th}$ wavelength, $T_i$ the tuning time of the RAUs to change the wavelength, $n_R(i)$ the number of RAUs that changed their wavelength to $i^{th}$ wavelength and $\Delta_{max}(i)$ the maximum RTT of the user from CO at $i^{th}$ wavelength. The traffic demands of the users change with time. So, to evenly distribute the load, the wavelength allocation repeats after a fixed $t_w$ time. If there is no change of the wavelength, then the next data transfer cycle length for a wavelength for single gate polling is calculated as given by Eq. (5).

Similarly, for multi-gate polling with the wavelength allocation, the data transfer cycle length is calculated as follows:

$$T_{cycle(i)} = \max \left\{ \frac{u_k(i) \times N_g(i) \times (2T_r + T_g)_i + n_R(i) \times T_i}{\Delta_{max} + N_g(i) \times u_k(i) \times T_g + n_R(i) \times T_i} \right\}$$  

(12)

Further, when there is no change of the wavelength, then the next data transfer cycle length for multi-gate polling is calculated as given by Eq. (6). In the DWA algorithm, we fix the wavelength cycle allocation length, and the wavelength allocation repeats after a fixed time. However, this approach may degrade the network performance by increasing the mean packet delay in self-similar traffic. Also, in the DWA algorithm, after a fixed $t_w$ time, the wavelength allocation repeats for the RAUs because of which the network performance suffers from an unnecessary penalty of tuning time, even when it could be avoided. Hence, we propose an ADWA algorithm in which the wavelength allocation cycle is as per the traffic demand.

2) ADWA ALGORITHM

In the ADWA algorithm, the initial wavelength allocation to all RAUs is done in the same fashion as in the DWA algorithm, such that the relative load on every wavelength is nearly $(1/N_\lambda)$, as shown in Fig. 8. For $N_\lambda$ wavelengths, there are $N_\lambda$ sessions running simultaneously, and the users access the wavelength on a time-sharing basis. After the initial wavelength allocation, the CO monitors the load on the wavelength after every data transfer cycle, as shown in Fig. 8. If the load on $j^{th}$ wavelength ($\rho_{\lambda,j}$) is greater than the threshold $\rho_{th}$, then the CO arranges all the RAUs in descending order according to their load. The CO moves highest loaded ($j^{th}$) RAU to $k^{th}$ wavelength if the relative load on that wavelength after accommodating the traffic requirements of the RAU, given by $(\rho_{\lambda,k} + F_\lambda(k)) / \sum_{i=1}^{N_\lambda} \rho_{\lambda,i}$, is less than $(1/N_\lambda)$. This process repeats until the load on $j^{th}$ wavelength becomes less than the threshold $\rho_{th}$ or the relative load on every other wavelength is $(1/N_\lambda)$. The cycle lengths are calculated similarly as explained in the DWA algorithm but with flexible $t_w$ time, which depends on the instantaneous traffic.

C. DELAY MODEL FOR RoF NETWORK

The network performance is usually analyzed with the mean packet delay. In this subsection, we propose a delay model to compute delay for the single and multiple wavelength architectures for the single-gate and multi-gate polling algorithms. The mean delay comprises of the delay introduced by the identification phase, data transfer phase and the delay in re-transmissions in case of the connection drop during handovers.
1) DELAY MODEL FOR SINGLE WAVELENGTH ARCHITECTURE

We propose the delay model for single wavelength architecture, considering the following delay components:

- **Delay in the identification phase**: The users cannot start the transmission of data packets before the identification phase is completed, therefore, it introduces additional delay penalty. The time elapsed in user identification is given by Eq. (2). The identification phase follows the registration phase, which repeats after \( t_{rg} \) time, as explained in the previous section.

- **Delay in handovers**: When the users move from one cell to another, there is a possibility of connection drop because of the unavailability of slots required to register the users in the cell. In such cases, the user has to wait for the next registration cycle to get identified in the cell and re-transmit the lost packets. This handover delay can be calculated as follows:

\[
d_{ho} = t_{rg} \times \sum_{k=0}^{\infty} k \times (1 - P_{CD}) \times p_k^{CD}
\]

where we calculate \( P_{CD} \) using Eq. (3).

- **Delay in data transfer phase**: The delay in the transfer of data packets for single-gate polling can be calculated as follows:

\[
d_{SG} = \frac{T_{cycle}}{2} \times (3 - \frac{\rho}{u})
\]

where \( T_{cycle} \) is calculated using Eq. (5). The data transfer delay for multi-gate polling is calculated as given below.

\[
d_{MG} = \max \left\{ \frac{N_g \times (2 + T_g) \times (3u - \rho)}{2 \times (1 - \rho)} \times \frac{T_{cycle}}{N_g}, \frac{T_{cycle}}{1.5 - \rho} + (\rho + \Delta_{max}) \right\}
\]

where for the high load, the number of gate messages to be sent in a cycle approaches 1, hence, we calculate the mean delay similar to the single-gate polling and is given by the first part of Eq. (15). However, for the low load, the second part of Eq. (15) influences the mean delay and we calculate \( T_{cycle} \) using the second part of Eq. (6).

Finally, we calculate the overall mean delay as follows:

\[
d_T = p_1 \times (T_{ID} + d_{ho}) + p_2 \times d_{tx}
\]

where \( d_{tx} \) is the data transfer delay, which is calculated using Eq. (14) or (15) depending on the type of polling algorithm. \( p_1 \) and \( p_2 \) are the probabilities of the system to be in the identification phase, and the data transfer phase, respectively.

The frame structure for the single wavelength architecture is as shown in Fig. 9a, where a registration frame comprises of identification and data transfer sub-frames. The registration frame length is given as below

\[
t_{rg} = T_{ID} + n_1 \times T_{cycle}
\]

where \( T_{ID} \) is the identification sub-frame length, which the CO send at the beginning of the registration frame, and we calculate this using Eq. (2). \( T_{cycle} \) is the data transfer sub-frame length, which we calculate depending on the type of polling algorithm, as explained earlier in this sub-section. \( n_1 \) is the average number of data transfer sub-frames in registration frame. We calculate \( n_1 \) as \( \lfloor (T_{rg} - T_{ID}) / T_{cycle} \rfloor \). Finally, we calculate \( p_1 \) as \( (T_{ID}/t_{rg}) \), and \( p_2 \) as \( (n_1 \times T_{cycle}/t_{rg}) \).

2) DELAY MODEL FOR MULTIPLE WAVELENGTH ARCHITECTURE

We propose a model to evaluate the mean delay for multiple wavelength architecture where wavelength allocation repeats after \( t_w \) time. The model comprises the delay in the data transfer phase, identification phase, and handovers. Note that the delay for the identification phase and handovers remains the same as calculated in the delay model for a single wavelength architecture. Further, we compute the delay in the data transfer phase. When there is wavelength allocation among RAUs for balanced traffic distribution, we consider the additional overhead of tuning time of the RAUs in the mean delay. The cycle length increases, when the CO allocates wavelength before the time frame allocation to the users considering single gate polling, which is calculated using Eq. (11) for a wavelength. Then, we calculate the average cycle length considering all the wavelengths. Finally, the data transfer delay is calculated as given by Eq. (14). Similarly, we calculate the data transfer delay for multi-gate polling, using Eqs. (12), and (15). Moreover, if there is no change in the wavelength allocation, then the mean delay for the data transfer is calculated by considering zero tuning time. We calculate the overall mean delay for multiple wavelength architecture as follows:

\[
d_T = p_1 \times (T_{ID} + d_{ho}) + p_2 \times d_{tx} + p_3 \times d_{k-tx}
\]

where \( d_{k-tx} \), and \( d_{tx} \) are the data transfer delay with and without the wavelength allocation, respectively, which is
calculated as explained above, depending on the type of polling algorithm. \( p_1 \) is the probability for the system to be in the identification phase, \( p_2 \) and \( p_3 \) are to be in the data transfer phase without and with wavelength allocation, respectively. The frame structure for the multiple wavelength architecture is as shown in Fig. 9b, where a registration frame comprises of identification sub-frame, wavelength allocation sub-frames and data transfer sub-frames. The registration frame length is given as below

\[
t_{rg} = T_{ID} + n_a \times (T_{cycle} + T_t) + n_b \times T_{cycle}
\]

where \( n_a \) and \( n_b \) are the average number of data transfer sub-frames with and without wavelength allocation. The identification sub-frame length and the data-transfer without wavelength allocation sub-frame length are calculated similarly as explained for single wavelength architecture. We calculate the length of data-transfer with wavelength allocation sub-frame length as \( (T_{cycle} + T_t) \). Then, we calculate \( n_a \) as \( \lceil (t_{rg} - T_{ID})/t_w \rceil \), and \( n_b \) using Eq. (19). Finally, we calculate \( p_1, p_2 \), and \( p_3 \) as \( (T_{ID}/t_{rg}), (n_b \times T_{cycle}/t_{rg}), \) and \( (n_a \times (T_{cycle} + T_t))/t_{rg} \), respectively.

In the DWA algorithm, the wavelength allocation repeats after a fixed \( t_w \) time. Whereas, in the ADWA algorithm, \( t_w \) depends on the instantaneous network load where we consider self-similar traffic. In self-similar traffic there is a burst of packets in the on-period, and no packets are generated in the off-period [27]. Further, the CO initiates the wavelength switching when the instantaneous load on a wavelength becomes more than the threshold, which happens when a minimum \( t_{on} \) users are in the on-period. Further, the relative change in the load on a wavelength, denoted by \( \delta \), is \( (\rho_{in} - \rho_{i})/\sum_{i=1}^{N_i} \rho_{i} \), where \( \rho_{i} \) is the average load on a wavelength, \( \delta \in [0, 1/N_\lambda] \), and \( \rho_{in} \) is the instantaneous load. We can also express \( \delta \) as \( [(\rho_{i} - (L_i/u_{on} \times R))] \). We calculate \( \rho_{in} \) and \( u_{on} \) for different values of \( \delta \). Then, the probability of a user to be in the on-period is given as \( p_{on} = \rho_{in} \times L_i / u_{on}(i) \times R) \), where \( L_i \) is the data rate per wavelength and \( R \) is the data rate per user. Then we calculate the probability of wavelength switching as given below

\[
p_{\lambda} = \sum_{i=u_{on}}^{u_{i}} \binom{u_{i}}{i} \times p_{on}^{i} \times (1 - p_{on})^{u_{i}-i}
\]

where \( u_{i} \) is the average number of users per wavelength. Further, the wavelength switching can take place only at the beginning of the data transfer cycle. Therefore, for different values of \( \delta \), we calculate the wavelength allocation time, \( t_w \) as follows:

\[
t_w(\delta) = \max \left\{ \frac{T_t + T_{cycle}}{T_{cycle} \times \sum_{k=1}^{n_{cycle}} (k - 1) \times (1 - p_{\lambda})^{k-1} \times p_{\lambda}} \right\}
\]

where \( n_{cycle} \) is the maximum number of data transfer cycles in a registration phase, which is expressed as \( \lceil (t_{rg} - T_{ID})/T_{cycle} \rceil \). After a wavelength allocation, the CO must carry out at least one data transfer cycle before allocating wavelengths again. Therefore, the minimum value of \( t_w \) is given by the first part of Eq. (21). Finally, we calculate the mean delay as explained earlier in this sub-section and find the value of \( \delta \) for which the mean delay is minimum.

### Table 2. Simulation Parameters for MAC Protocol for the RoF Networks

| Parameter                        | Value   |
|----------------------------------|---------|
| Maximum no. of RAUs             | 8       |
| Maximum fiber length            | 35 km   |
| Maximum number of wavelengths   | 4       |
| Size of REPORT and GATE messages| 64 bytes|
| Speed of users                  | 100 km/h|
| Line rate per wavelength        | 1 Gb/s  |
| Guard time                      | 1 \(\mu\)s |
| Maximum grant limit to a user    | 15000 bytes |
| Tuning time of the RAUs         | 1 ms    |

**V. PERFORMANCE EVALUATION**

In this section, we present the performance of the proposed MAC protocol for the RoF networks. We simulate the RoF network model in OMNeT++, and analyzed the performance by varying the network load. We consider single and multiple wavelength network architectures to simulate these models. The network’s simulation comprises a CO that is connected to 8 RAUs through an optical fiber. Further, the RAUs are connected to mobile users present in their cell by the wireless link. In this model, we consider the maximum optical fiber length as 35 km. We consider 20 users per wavelength. Other simulation parameters for the MAC protocol for an RoF network are given in Table 2. We analyze the results based on the mean packet delay and the packet loss rate of the network by varying the normalized network load. We consider the Poisson and self-similar network traffic for the simulations. Further, for self-similar traffic, we consider a shape parameter of 1.4 and 1.2 for the on-period and the off-period, respectively [12].

We investigate the probability of connection drop when a user moves from one cell to another by varying the number of slots per RAU. We consider that 10% of the slots per RAU, available per cell in the control and signaling channel, are reserved for handovers [28]. As the number of slots available per RAU increases, the probability of connection drop decreases for the same number of users in the network as more users can be accommodated in a cell, and there are fewer chances of a connection drop. However, the increase in the number of slots increases the length of the identification phase. For the computation of mean delay, we consider the number of slots in the identification frame for which the probability of connection drop is not more than 1%. We obtain the number of slots as 10 and 15 per RAU to accommodate users in single wavelength and multiple wavelength architectures, respectively. In this section, we analyze the performance of RoF network for Poisson and self-similar traffic. We verify the proposed analytical model for Poisson traffic with the...
results obtained from simulations. Further, after validating our proposed algorithms for Poisson traffic, we present the simulation results for self-similar traffic.

A. RESULTS FOR POISSON TRAFFIC

In this sub-section, we present the mean packet delay for single-gate and multi-gate polling with single and multiple wavelength RoF network architectures for Poisson traffic. In Fig. 10, we observe that the mean delay for the multi-gate polling is less than the single-gate polling for single wavelength architecture as the formation of voids is much less in multi-gate polling. Besides, we send REPORT message before the transmission of data packets. Hence, the CO is informed earlier about the user’s traffic requirements and can send the GATE message to a user even before all previous sub-cycle data packets are received. This approach results in decreased mean delay. The mean delay for the multi-gate polling is within the bound of 1 ms for all load values.

For multiple wavelength architecture, we use the DWA algorithm with wavelength allocation cycle length fixed at 0.1 s as the mean delay is least for this value, as shown in Fig. 10b. We observe that when \( t_w \) is very less (0.01 s), the overhead of tuning the RAUs to another wavelength increases, which results in the increase of the overall mean delay. However, when \( t_w \) is very large (1 s), the performance degrades at high load because of the unbalanced load distribution on the wavelengths. In Fig. 10, we observe that for multi-gate polling the mean delay is within the bounds of 1 ms for the normalized load below 0.7 (practical load scenario) for \( t_w \) as 0.1 s. In contrast, single-gate polling cannot satisfy these limitations. Moreover, the results obtained from simulations are very close to the proposed analytical delay model. The ADWA algorithm does not have any significant effect on the mean delay for multiple wavelength architecture for the Poisson traffic as the users do not generate the bursts of packets, hence there is no sudden increase in the instantaneous traffic. Therefore, we analyze the performance of the ADWA algorithm for self-similar traffic only, which is explained in detail in the next sub-section.

Further, we compare the proposed algorithms with the state-of-the-art algorithms, like MIP [21], MT-MAC [18], and gMT-MAC [29] for Poisson traffic, as shown in Fig. 10. The performance of the single-gate polling for single wavelength architecture is similar to the MIP algorithm. However, multi-gate polling performs better than the MIP algorithm. Further, MT-MAC offers higher delay than the proposed algorithms, as it uses a fixed grant-sizing approach and does not consider the user demands. Moreover, in MT-MAC and gMT-MAC, the CO performs the identification phase more frequently than the proposed algorithms, which increases the overall mean delay up to practical normalized load of 0.7. Hence, the proposed algorithms perform better than state-of-the-art algorithms.

B. RESULTS FOR SELF-SIMILAR TRAFFIC

We analyze the proposed algorithms for self-similar traffic, as shown in Fig. 11. In multiple wavelength
architectures, we consider the ADWA algorithm. We take the value of δ as 0.1, as the mean delay is the least in that case. We observe similar trends for the self-similar traffic. For the single wavelength architecture, at a normalized load of below 0.7, the mean delay for multi-gate polling is within the bound of 1 ms. For multiple wavelength architecture, this performance can be achieved for the normalized load below 0.6. Hence, the single wavelength architecture performs better than multiple wavelength architecture. The use of multiple wavelengths, however, increases the overall capacity of the system by increasing the data rate, and hence more users can be served. However, the tuning time of RAUs leads to some delay penalties when a new wavelength is allocated to it. We can still not achieve the delay within the bounds of 1 ms for normalized load greater than 0.5, as shown in Fig. 11a. Finally, in Fig. 11b, we show the packet loss rate for single-gate and multi-gate polling with single and multiple wavelength architectures. Further, we can infer throughout of the network from packet loss rate. We observe that for multi-gate polling the packet loss rate is within the bounds of 1% for a practical load of 0.5, for both single and multiple wavelength architectures. However, we do not achieve this performance using single-gate polling for multiple wavelength architecture.

The multi-gate polling performs better than single gate polling, as explained earlier in this section. Hence, we simulate the ADWA algorithm for multi-gate polling. We consider the different levels of bursty traffic for the simulations. To generate the different level of burstiness, we consider that in the on-period of self-similar traffic, the packet arrivals are exponentially distributed with a mean arrival rate of 0.009 Mb/s and 12.5 Mb/s for less and highly bursty traffic.
bursty traffic, respectively for all loads [30]. We present the results for less and highly bursty traffic in Fig. 12 by varying deviation in the relative load at a wavelength (δ) for different tuning time. We show that the values of δ do not affect the mean delay significantly when the tuning time is 100 µs, due to the faster wavelength switching. Further, for higher tuning time of 1 ms and 10 ms, we show that, for very small values of δ (e.g., 0.01 and 0.05), the wavelength allocation cycle repeats frequently, and because of the overhead of tuning time and control messages, the channel utilization decreases which increases the mean delay. When the value of δ is very high (e.g., 0.2), the wavelength allocation cycle length increases. Due to the unbalanced load distribution among the wavelengths, the mean delay for high loaded wavelength increases, which increases the overall mean delay. We also analyze the variations in the mean delay with the deviation in the relative load (δ) at a wavelength.

In Figs. 13a and 13b for less and highly bursty traffic, respectively, we show that at a normalized load of 0.5, the best performance is achieved when the value of δ is 0.15 for less bursty traffic and 0.1 for highly bursty traffic. In highly bursty traffic, as the network response should be faster to balance the overall traffic among all the wavelengths, the optimum value of δ is smaller than for the less bursty traffic which shortens the wavelength allocation cycle length.

VI. CONCLUSION

This paper proposed a converged MAC protocol for RoF networks for single and multiple wavelength RoF network architectures with single and multi-gate polling. Further, for multiple wavelength architecture, we proposed DWA and ADWA algorithms to allocate wavelength to the RAUs. We presented that the proposed algorithm significantly improves the delay performance compared to the state-of-the-art algorithm for single wavelength architecture. Further, we showed that multiple wavelength architecture could serve more users. The mean delay, however, is higher than in single wavelength architecture because of the increase in overheads due to the tuning time. However, optimum performance can be achieved with the proposed ADWA algorithm. Finally, we proposed an analytical delay model considering identification, handovers, and data transfer delay and verified it with simulations. Therefore, it is concluded that the multi-gate polling with multiple wavelength RoF network architecture is the right solution for the evolution of the next-generation high-speed networks.

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KSHITIZA SINGH received the M.Tech. degree in wireless communication and computing from the Indian Institute of Information Technology, Allahabad, in 2015. She is currently pursuing the Ph.D. degree with the Department of Electrical Engineering, IIT Delhi, India, with Government Fellowship (MeitY). Her research interests include optical access networks and optical wireless communication systems and networks.

ABHISHEK DIXIT received the M.Tech. degree in opto-electronics and optical communication from Ghent University, Belgium, in 2014. He was a Postdoctoral Researcher with Ghent University, in 2015. He is currently an Assistant Professor with the Department of Electrical Engineering, IIT Delhi. He was involved in several European projects, like IST-OASE, Alpha, and GreenTouch and government-funded sponsored projects, like Converged Optical Network Evolution (CONE) from the Department of Science and Technology, LiFi Networks from the Department of Telecommunications, and consultancy projects from CEL and FTTH Council Asia Pacific. He has more than 51 national and international publications, both in journals and proceedings of conferences. He has also offered a 14-week online Nptel course on Principles of Digital Communications. His research interests include lightwave, broadband optical access networks, and optical wireless communication systems and networks. He received the Early Career Research Award, in 2016.

VIRANDER KUMAR JAIN received the Ph.D. degree in communication engineering from the Indian Institute of Technology Delhi (IITD), New Delhi, India, in 1982. From 1978 to 1982, he was with the Research Department, All India Radio, New Delhi. Since 1982, he has been on the faculty of Electrical Engineering Department, IITD. He was with BTRL, U.K., from January 1988 to June 1988, German Aerospace Research Establishment (DLR), Germany, from February 1991 to January 1992 and from April 1995 to June 1995, Fachhochschule Düsseldorf (FHD), Fachbereich Elektrotechnik, Düsseldorf, Germany, from January 1995 to March 1995 and from November 1998 to December 1998, Fondazione Ugo Bordoni (FUB), Rome, Italy, from September 1998 to July 1999. He has been a Visiting Professor with the Department of Electrical Engineering, University of Applied Sciences, Düsseldorf, Germany, from 2002 to 2003, and Department of Electrical and Electronics Engineering, Universiti Teknologi Petronas (UTP), Malaysia, from 2008 to 2010. After superannuation in 2017, he is currently an Emeritus Professor with IITD. He has published more than 180 research papers/reports in national and international journals and conferences. He has coauthored three books: Optical Communication Systems, published jointly by (Narosa Publishing House and John Wiley, 1996), Optical Communications: Components and Systems, (Narosa Publishing House, 2000), and Free Space Optical Communication, (Springer Nature, 2017). His research interests include noise study and modeling, digital communications, data communications, optical communications, and networks.

Dr. Jain is a fellow of the Institution of Electronics and Telecommunication Engineers (IETE) and a Life Member of the Indian Society for Technical Education (ISTE). He has received Silver Jubilee Award for the bestselling author on his second book in the year 2002. He was a recipient of the British Government TCTP Award, an Associate Membership, AS-ICTP, Trieste, Italy, from 1988 to 1995, the Alexander von Humboldt Fellowship, Germany; and the DAAD International Long Term Guest Lectureship, Germany.

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