DESIGN OF MEDIUM ACCESS CONTROL PROTOCOLS FOR RADIO-OVER-FIBER NETWORKS

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Certificate

This is to certify that the thesis entitled **"Design of Medium Access Control Protocols for Radio-over-Fiber Networks"**, being submitted by **Kshitiza Singh** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the bonafide research work carried out by her under our supervision and guidance. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Abstract

The oncoming Internet-of-things applications and smart machine-to-machine communication lead to an enormous increase in network traffic. To meet the escalating demands of these time-critical applications, a wireless network that has an optical backbone with a colossal bandwidth capacity is required, for which the radio-over-fiber (RoF) technology is a promising candidate. To accomplish this goal, we propose RoF network architectures to support single and multiple wavelengths with simple and cost-effective remote antenna units (RAUs). Moreover, we propose a medium access control (MAC) protocol for the proposed RoF architectures, in which a central office (CO) registers and identifies the users in the network and distributes resources for the data transfer. In this work, we propose single-gate and multi-gate polling algorithms for the time frame allocation to the users. Further, we propose dynamic wavelength allocation algorithms to distribute the wavelengths among the RAUs according to the traffic generated by them. Moreover, we present 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.

Further, the RoF networks need to support the stringent delay requirements of the time-critical applications for a high density of mobile users in the network. However, the existing user registration and identification approaches for these networks mostly use a random access-based approach, which is not efficient for a high user density and cannot keep the overall mean delay within the permissible limit for such applications. In this thesis, we present a MAC protocol for the RoF network, for which we propose hybrid user identification and neighbor-aware hybrid user identification algorithms. Further, we propose an analytical delay model for the MAC protocol, which gives overall end-to-end mean delay considering the hybrid user identification approach and data transfer. Moreover, the results obtained from the analytical model closely follow the simulation results and the proposed algorithms are able to maintain the stringent delay thresholds for both low and high user densities.

Furthermore, in this work, we introduce a very small cellular (referred to as atto-cellular) RoF network, which can maintain a delay threshold of 10 μs to serve the futuristic robotic applications. An atto-cell is a radio cell typically less than 1 m^2

with antennas integrated into the floor tiles. For this network, we propose several architectures for the backbone network using RoF-based technology. To support these architectures, we consider the MAC protocol for the RoF network, which uses a simple polling approach for the data transfer. Further, we compute the splitting ratio for various cell sizes based on the network load for a delay requirement of 10 μs. We propose an analytical model for the same to validate the results obtained from the simulations. Finally, we present the cost analysis of atto-cellular RoF architectures. Based on this, we give some general design recommendations for the RoF network.

In the modern digital world, quality-of-experience (QoE) has become the central area of concern to ensure end-to-end user satisfaction. In this thesis, we analyze the quality-of-service (QoS) for different traffic classes for the RoF network. For this, we consider a simple and gated polling algorithm for the data transfer with dynamic weighted queuing for the queues of different traffic classes for the RoF networks comprising of atto-cells and micro-cells, respectively. The aforementioned polling approaches maintain a delay within the maximum bounds for high and medium priority traffic classes with high channel utilization. Further, we propose a model to map QoE with the QoS parameters, like delay, jitter, and packet loss rate, and quantify QoE by representing the degree of user satisfaction by a mean opinion score.

सार

आने वाले इंटरनेट-ऑफ-थिंग्स एप्लिकेशन और स्मार्ट मशीन-टू-मशीन संचार से नेटवर्क ट्रैफ़िक में भारी वृद्धि हुई है। इन समय-महत्वपूर्ण अनुप्रयोगों की बढ़ती मांगों को पूरा करने के लिए, एक वायरलेस नेटवर्क जिसमें एक विशाल बैंडविड्थ क्षमता के साथ एक ऑप्टिकल नेटवर्क होती है, जिसके लिए रेडियो-ओवर-फाइबर (RoF) तकनीक एक आशाजनक उम्मीदवार है। इस लक्ष्य को पूरा करने के लिए, हम सरल और लागत प्रभावी रिमोट एंटीना इकाइयों (RAU) के साथ एकल और एकाधिक तरंग दैर्ध्य का समर्थन करने के लिए RoF नेटवर्क आर्किटेक्चर का प्रस्ताव करते हैं। इसके अलावा, हम प्रस्तावित RoF आर्किटेक्चर के लिए एक माध्यम अभिगम नियंत्रण (MAC) प्रोटोकॉल का प्रस्ताव करते हैं, जिसमें एक केंद्रीय कार्यालय (CO) नेटवर्क में उपयोगकर्ताओं को पंजीकृत करता है और पहचानता है और डेटा ट्रांसफर के लिए संसाधन वितरित करता है। इस काम में, हम उपयोगकर्ताओं के लिए समय सीमा आवंटन के लिए सिंगल-गेट और मल्टी-गेट पोलिंग एल्गोरिदम का प्रस्ताव करते हैं। इसके अलावा, हम RAU के बीच तरंग दैर्ध्य को उनके द्वारा उत्पन्न ट्रैफ़िक के अनुसार वितरित करने के लिए गतिशील तरंग दैर्ध्य आवंटन एल्गोरिदम का प्रस्ताव करते हैं।

इसके अलावा, हम सिंगल-गेट और मल्टी-गेट पोलिंग एल्गोरिदम के लिए उपयोगकर्ता की पहचान और डेटा ट्रांसफर देरी पर विचार करते हुए सिंगल और मल्टीपल वेवलेंथ आर्किटेक्चर के लिए एक विश्लेषणात्मक विलंब मॉडल प्रस्तुत करते हैं। हम इसे सिमुलेशन से प्राप्त परिणामों के साथ सत्यापित करते हैं। इसके अलावा, RoF नेटवर्क में मोबाइल उपयोगकर्ताओं के उच्च घनत्व के लिए समय-महत्वपूर्ण अनुप्रयोगों की कठोर विलंब आवश्यकताओं का समर्थन करने की आवश्यकता है। हालांकि, इन नेटवर्कों के लिए मौजूदा उपयोगकर्ता पंजीकरण और पहचान दृष्टिकोण ज्यादातर एक यादृच्छिक पहुंच-आधारित दृष्टिकोण का उपयोग करते हैं, जो उच्च उपयोगकर्ता घनत्व के लिए कुशल नहीं है और ऐसे अनुप्रयोगों के लिए अनुमेय सीमा के भीतर समग्र औसत विलंब को नहीं रख सकता है। इस थीसिस में, हम RoF नेटवर्क के लिए एक MAC प्रोटोकॉल प्रस्तुत करते हैं, जिसके लिए हम हाइब्रिड उपयोगकर्ता पहचान और पड़ोसी-जागरूक हाइब्रिड उपयोगकर्ता पहचान एल्गोरिदम का प्रस्ताव करते हैं। इसके अलावा, हम MAC प्रोटोकॉल के लिए एक विश्लेषणात्मक विलंब मॉडल का प्रस्ताव करते हैं, जो हाइब्रिड उपयोगकर्ता पहचान दृष्टिकोण और डेटा ट्रांसफर को ध्यान में रखते हुए एक समग्र एंड-टू-एंड माध्य विलंब देता है। इसके अलावा, विश्लेषणात्मक मॉडल से प्राप्त परिणाम सिमुलेशन परिणामों का बारीकी से पालन करते हैं और प्रस्तावित एल्गोरिदम निम्न और उच्च उपयोगकर्ता घनत्व दोनों के लिए कड़े विलंब सीमा को बनाए रखने में सक्षम हैं।

इसके अलावा, इस काम में, हम एक बहुत छोटा सेलुलर (एटो-सेलुलर के रूप में संदर्भित) RoF नेटवर्क पेश करते हैं, जो भविष्य के रोबोट अनुप्रयोगों की सेवा के लिए 10 µs की देरी सीमा को बनाए रख सकता है। एक एटो-सेल एक रेडियो सेल है जो आमतौर पर फर्श टाइल्स में एकीकृत एंटेना के साथ 1 m^2 से कम होता है। इस नेटवर्क के लिए, हम RoF-आधारित तकनीक का उपयोग करके बैकबोन नेटवर्क के लिए कई आर्किटेक्चर प्रस्तावित करते हैं। इन आर्किटेक्चर का समर्थन करने के लिए, हम RoF नेटवर्क के लिए MAC प्रोटोकॉल पर विचार करते हैं, जो डेटा ट्रांसफर के लिए एक सरल मतदान दृष्टिकोण का उपयोग करता है। इसके अलावा, हम 10 µs की देरी की आवश्यकता के लिए नेटवर्क लोड के आधार पर विभिन्न सेल आकारों के लिए विभाजन अनुपात की गणना करते हैं। हम सिमुलेशन से प्राप्त परिणामों को मान्य करने के लिए उसी के लिए एक विश्लेषणात्मक मॉडल का प्रस्ताव करते हैं। अंत में, हम एटो-सेलुलर RoF आर्किटेक्चर का लागत विश्लेषण प्रस्तुत करते हैं। इसके आधार पर, हम RoF नेटवर्क के लिए कुछ सामान्य डिज़ाइन अनुशंसाएँ देते हैं।

आधुनिक डिजिटल दुनिया में, अनुभव की गुणवत्ता (QoE) एंड-टू-एंड उपयोगकर्ता संतुष्टि सुनिश्चित करने के लिए चिंता का केंद्रीय क्षेत्र बन गया है। इस थीसिस में, हम RoF नेटवर्क के लिए विभिन्न ट्रैफ़िक वर्गों के लिए सेवा की गुणवत्ता (QoS) का विश्लेषण करते हैं। इसके लिए, हम क्रमशः एटो-सेल और माइक्रो-सेल वाले RoF नेटवर्क के लिए विभिन्न ट्रैफ़िक वर्गों की कतारों के लिए गतिशील भारित कतार के साथ डेटा ट्रांसफर के लिए एक सरल और गेटेड पोलिंग एल्गोरिदम पर विचार करते हैं। उपरोक्त मतदान दृष्टिकोण उच्च चैनल उपयोग के साथ उच्च और मध्यम प्राथमिकता वाले यातायात वर्गों के लिए अधिकतम सीमा के भीतर देरी को बनाए रखते हैं। इसके अलावा, हम QoE को देरी, जिटर और पैकेट हानि दर जैसे QoS मापदंडों के साथ मैप करने के लिए एक मॉडल का प्रस्ताव करते हैं, और औसत राय स्कोर द्वारा उपयोगकर्ता संतुष्टि की डिग्री का प्रतिनिधित्व करके QoE की मात्रा निर्धारित करते हैं।

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Abbreviations

ACK	Acknowledgment
ADC	Analog-to-Digital Convertor
ADWA	Adaptive Dynamic Wavelength Allocation
AMGAV	Adaptive Multi-Gate polling with Void filling
A-RoF	Analogue Radio-over-Fiber
AWG	Arrayed Waveguide Grating
CapEx	Capital Expenditure
CO	Central Office
CoMP	Coordinated Multi-Point
CoS	Classes-of-Service
C-RAN	Cloud Radio Access Network
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear-to-Send
DAC	Digital-to-Analog Convertor
DAS	Distributed Antenna System
DBA	Dynamic Bandwidth Allocation
DIFS	Distributed Coordination Function Inter Frame Space
D-RoF	Digital Radio-over-Fiber
DWA	Dynamic Wavelength Allocation
eMBB	Enhanced Mobile Broadband
E/O	Electrical-to-Optical
EPON	Ethernet Passive Optical Network
FSO	Free Space Optical

FSK	Frequency Shift Keying
gMT-MAC	Gated Medium Transparent Medium Access Control
GPON	Gigabit Passive Optical Network
IoT	Internet-of-Things
IPACT	Interleaved Polling with Adaptive Cycle Time
KPI	Key Performance Indicator
LED	Light Emitting Diode
LoS	Line-of-Sight
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control
MEC	Moving Extended Cell
MIMO	Multiple Input Multiple Output
MOS	Mean Opinion Score
MT-MAC	Medium Transparent Medium Access Control
NOMA	Non-Orthogonal Multiple Access
O/E	Optical-to-Electrical
OFDM	Orthogonal Frequency Division Multiplexing
PIC	Photonic Integrated Circuit
PS	Power Splitter
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoE	Quality-of-Experience
QoS	Quality-of-Service
RAU	Remote Antenna Unit

RF	Radio Frequency
R&F	Radio & Fiber
RoF	Radio-over-Fiber
RTS	Request-to-Send
RTT	Round Trip Time
SOA	Semiconductor Optical Amplifier
SIFS	Short Inter Frame Space
TDMA	Time Division Multiple Access
THO	Traditional Handover
URLLC	Ultra-Reliable and Low Latency Communication
VCZ	Virtual Cellular Zone
VLC	Visible Light Communication
WSN	Wireless Sensor Network
4G	Fourth-Generation
5G	Fifth-Generation

Symbols

u	Total number of users in the network
u_λ	Average number of users per wavelength
N_λ	Number of wavelengths in the network
N_R	Number of RAUs in the network
$u_R(i)$	Number of users in the cell of i^{th} RAU
$n_R(i)$	Number of RAUs that changed their wavelength to i^{th} wavelength
c_s	Number of slots for control and signaling
h	Number of slots for control and signaling reserved for handovers
F_s	Number of slots in identification frame
N_g	Number of GATE messages to be sent to every user in a data transfer cycle in multi-gate polling
n_b	Number of beacon messages transmitted by a user in the neighbor discovery phase
$u_w(i)$	Number of users in the cells of RAUs tuned to i^{th} wavelength
u_R^p	Number of previous users in the RAU's cell
u_R^n	Number of newly arrived users in the RAU's cell
u_R	Average number of users present in a RAU's cell
u_t	Number unresolved users attempting transmission after receiving the POLL frame
u_s	Number of users which successfully transmit the REPLY packet in an identification frame
$E[u_s]$	Average number of successful users in each POLL frame
c_n	Number of clusters in the cell of an RAU
u_c	Average number of contending users per cluster
u_d	User density
n_{RF}	Number of radio frequencies

$n_{sp}(i)$	Average number of users in i cells
$n_{min}(i)$	Minimum number of users per RF out of j users in i cells for load balancing
$n_{max}(i)$	Maximum number of users per RF out of j users in i cells for load balancing
B_s	Buffer size
λ_n, λ_{ho}	Arrival rates of existing users and the users after handover, respectively
μ_n, μ_{ho}	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 message
T_{ACK}	Time to send the ACK message
Δ_{max}	Maximum RTT between the CO and a user
t_w	Time after which the wavelength allocation repeats
T_t	Time required by an RAU to tune its transceivers to another wavelength
T_{cycle}	Length of data transfer cycle
T_{IF}	Length of a contention round in an identification frame
T_{rp}	Time required to send REPLY packet
L_b	Time between the transmission of the successive beacon message
T_b	Time required to transmit a beacon message
T_{res}	Time required to transmit a response message
d_{nd}	Neighbor discovery delay
d_{SG}, d_{MG}	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
$d_{\lambda-tx}, d_{tx}$	Data transfer delay with and without the wavelength allocation, respectively
$E[d_{ID}^n(i)]$	Expected mean delay of successful REPLY packet reception at the CO at i^{th} attempt
d_{DT}	Mean data transfer delay
d_{ID}	Mean identification delay
d_{th}	Delay threshold to compute splitting ratio
$d_j^\alpha(i)$	Mean delay considering α users in a cell out of j users in i cells
$d_{n_j}^i$	Mean delay considering n_j users in a cell

$d_{eff}(i)$	Effective delay considering j users in i cells
P_{CD}	Probability of connection drop
p_{on}	Probability of a user to be in the on-period for self-similar traffic
p_{λ}	Probability of wavelength switching in ADWA algorithm
$P_s(u_t, u_s)$	Probability of u_t users attempt to transmit and u_s users successfully transmit in a unique slot in a POLL frame
p_s	Probability of successful transmission by a user in a POLL frame
$P_{succ}(i)$	Probability of successful transmission in i^{th} POLL frame
$P_c(c_n)$	Probability of having c_n clusters in the RAU's cell
$p_{pr}(i)$	Probability of i users being in the same cell as in the previous identification phase
$p_n(i)$	Probability of i newly arrived users in a cell
$p_j^{\alpha}(i)$	Probability of finding j users in i cells
ρ	Normalized network load
ρ_{in}	Instantaneous load on a wavelength
δ	Relative change in the load on a wavelength for self-similar traffic
L_{λ}	Data rate per wavelength
R	Data rate per user
η	Splitting ratio
β	Acceptable loss in the splitting