MEDIUM ACCESS CONTROL LAYER ISSUES IN OPTICAL WIRELSS COMMUNICATION

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Dedicated to Saksham & Munish…

Certificate

This is to certify that the thesis entitled **"Medium Access Control Layer Issues In Optical Wireless Communication"** being submitted by **Mrs. Monica Bhutani** to the **Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi,** for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by her under our supervision. 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

Optical wireless communication (OWC) has evolved as a potential addition to existing wireless technologies owing to its high capacity, security, and unlicensed spectrum. In addition, as optoelectronic components have matured and the industry has become more globalized, OWC has evolved as a possible solution to future bandwidth demands and the "border mile bottleneck." As a result of the projected limitation of the wireless frequency spectrum, researchers have turned to OWC, which has evolved as significant support for Wi-Fi.

The IEEE 802.15.7 standard, published in 2011, employs visible light wavelengths from 380nm to 780nm to carry data sufficiently to enable audio and video multimedia services while adhering to proper eye safety requirements. The proposal's recommendations address the mobility of transparent connections, compatibility with visible-light structures, interference, and noise from other sources, such as ambient light. The regulation uses only the visible portion of the light and supports only the downlink. Hence the baseline technology was named visible light communication (VLC). The standard was amended in 2018 to include light energy for downstream communication and infrared spectrum for upstream transmission, as well as proposed physical (PHY) and media access layer (MAC) layers for OWC-based systems to provide bidirectional communication. This version employs a visible portion of the light for downlink and IR for uplink.

Although significant research has been conducted on the PHY layer, the MAC layer must be adapted to application-specific requirements. This research provides an overview of the critical technologies required to understand OWC technology. This work looks at MAC layer challenges in OWC, such as performance modeling, guaranteed time

slot (GTS) resource allocation, emergency data handling, and energy consumption analysis. A thorough literature review is conducted to identify the MAC layer challenges impeding the mainstream adoption of green wireless communication technology.

Throughput is a crucial barrier for the VLC personal area network (VPAN) because it significantly influences the network performance. We introduce a unique Markov chain model with two distinct channel assessments, representing a substantial advancement in improving network throughput for a VPAN with a star topology. The work enhances the state-of-the-art analytical models for the MAC layer, allowing VPAN performance to be efficiently planned and forecasted. We also thoroughly evaluate other network characteristics, such as network collision probability and end-to-end epoch, to demonstrate the applicability of the suggested model. We validate the model's analytical results with extensive MATLAB simulations and obtain realistic estimations, especially for substantial network sizes.

Furthermore, the Internet expands as more bandwidth-intensive apps and network sensors are introduced, resulting in spectrum limits. Because it uses an unlicensed terahertz spectrum, is resistant to radio frequencies, and is more secure to install, the IEEE 802.15.7 standard offers OWC as a resolution. However, the standard does not address sensor flexible data requirements or priority data transmission, which are the critical quality of service requirements. Our research focuses on the latency, adaptive traffic management, and overall network throughput of wireless sensors as they become increasingly widespread in personalized medical health care. We demonstrate a unique superframe structure allowing adaptive data management sleep mode. The suggested superframe structure is simulated throughout both the contention access period (CAP) and contention-free time (CFP). The proposed technique operates in a hybrid mode, combining the carrier sense multiple access (CSMA/CA) and GTS allocation algorithms.

By comparing it to IEEE 802.15.7, we demonstrate the proposed work's significance with respect to latency and throughput. According to the simulation results, both components have greatly improved. Furthermore, the collision probability of our proposed adaptive superframe structure is calculated.

Although biosensors are becoming more common in the medical field, battery life remains a crucial hurdle to widespread implementation. These sensors heavily rely on radio frequency technology, which is detrimental to human health and the environment. We provide a battery-efficient adaptive superframe for real-time biosensors based on OWC. This retrofit strategy reduces transmission delays while increasing energy efficiency. Additionally for wearable sensors, the one-of-a-kind continuous superframe construction conserves the battery while enabling emergency data handling via the deployment of an emergency beacon. We have assessed the feasibility of our suggested solution by contrasting the simulation results to the IEEE 802.15.7 standard superframe timeline. End-to-end delays, average energy usage, and savings are predicted and analyzed using analytical expressions. The findings reveal a significant improvement in energy savings and delays with no additional overheads.

सार

ऑप्टिकल वायरलेस कम्युनिकेशन (ओडब्ल्यूसी) अपनी उच्च क्षमता, सुरक्षा और बिना लाइसेंस वाले स्पेक्ट्रम के कारण मौजूदा वायरलेस प्रौद्योगिकियों के संभावित अतिरिक्त के रूप में उभरा है। चूंकि ऑप्टोइलेक्ट्रॉनिक घटक परिपक्व हो गए हैं और उद्योग अधिक वैश्वीकृत हो गया है, ओडब्ल्यूसी भविष्य की बैंडविड्थ मांगों और "सीमा मील की अड़चन" के संभावित समाधान के रूप में उभरा है। वायरलेस फ्रीक्वेंसी स्पेक्ट्रम की अनुमानित सीमा के परिणामस्वरूप, शोधकर्ताओं ने OWC की ओर रुख किया है, जो वाई-फाई के लिए महत्वपूर्ण समर्थन के रूप में विकसित हुआ है।

आईईईई 802.15.7 मानक, 2011 में जारी किया गया, उचित नेत्र सुरक्षा आवश्यकताओं का पालन करते हुए ऑडियो और वीडियो मल्टीमीडिया सेवाओं को सक्षम करने के लिए डेटा को पर्याप्त रूप से ले जाने के लिए 380 एनएम से 780 एनएम तक दृश्य प्रकाश तरंग दैर्ध्य को नियोजित करता है। प्रस्ताव की सिफारिशें पारदर्शी कनेक्शन की गतिशीलता, दृश्य-प्रकाश संरचनाओं के साथ संगतता, हस्तक्षेप, और परिवेश प्रकाश जैसे अन्य स्रोतों से शोर को संबोधित करती हैं। विनियमन केवल प्रकाश के दृश्य भाग का उपयोग करता है और केवल डाउनलिंक का समर्थन करता है। इसलिए बेसलाइन तकनीक को विजिबल लाइट कम्युनिकेशन (वीएलसी) नाम दिया गया। डाउनस्ट्रीम संचार के लिए प्रकाश ऊर्जा और अपस्ट्रीम ट्रांसमिशन के लिए इन्फ्रारेड

स्पेक्ट्रम, साथ ही ओडब्ल्यूसी-आधारित सिस्टम के लिए प्रस्तावित भौतिक (पीएचवाई) और मीडिया एक्सेस लेयर (मैक) परतों को द्विदिश संचार प्रदान करने के लिए मानक में संशोधन किया गया था। यह संस्करण डाउनलिंक के लिए प्रकाश के दृश्य भाग और अपलिंक के लिए आईआर को नियोजित करता है।

यद्यपि PHY परत पर महत्वपूर्ण शोध किया गया है, MAC परत को अनुप्रयोग-विशिष्ट आवश्यकताओं के लिए अनुकूलित किया जाना चाहिए। यह शोध OWC प्रौद्योगिकी को समझने के लिए आवश्यक महत्वपूर्ण तकनीकों का अवलोकन प्रदान करता है। यह कार्य OWC में MAC परत चुनौतियों को देखता है, जैसे कि प्रदर्शन मॉडलिंग, गारंटीकृत समय स्लॉट (GTS) संसाधन आवंटन, आपातकालीन डेटा हैंडलिंग और ऊर्जा खपत विश्लेषण। हरित वायरलेस संचार प्रौद्योगिकी की मुख्यधारा को अपनाने में बाधा उत्पन्न करने वाली MAC परत चुनौतियों की पहचान करने के लिए एक संपूर्ण साहित्य समीक्षा की जाती है।

वीएलसी पर्सनल एरिया नेटवर्क (वीपीएएन) के लिए थ्रूपुट एक महत्वपूर्ण बाधा है क्योंकि यह सीधे नेटवर्क प्रदर्शन को प्रभावित करता है। हम दो अलग चैनल आकलन के साथ एक अद्वितीय मार्कोव चेन मॉडल पेश करते हैं, जो एक स्टार टोपोलॉजी के साथ एक वीपीएन के लिए नेटवर्क थ्रूपुट में सुधार करने में पर्याप्त प्रगति का प्रतिनिधित्व करता है। मैक परत के लिए अत्याधुनिक विश्लेषणात्मक मॉडल पर काम में सुधार होता है, जिससे VPAN प्रदर्शन को कुशलता से नियोजित और पूर्वानुमानित किया जा सकता है। हम प्रस्तावित मॉडल की प्रयोज्यता को स्पष्ट

करने के लिए अन्य नेटवर्क विशेषताओं, जैसे नेटवर्क टकराव की संभावना और एंड-टू-एंड युग का भी अच्छी तरह से मूल्यांकन करते हैं। हम व्यापक MATLAB सिमुलेशन के साथ मॉडल के विश्लेषणात्मक परिणामों को मान्य करते हैं और यथार्थवादी अनुमान प्राप्त करते हैं, विशेष रूप से पर्याप्त नेटवर्क आकारों के लिए।

इसके अलावा, इंटरनेट का विस्तार होता है क्योंकि अधिक बैंडविड्थ-गहन ऐप्स और नेटवर्क सेंसर पेश किए जाते हैं, जिसके परिणामस्वरूप स्पेक्ट्रम सीमाएं होती हैं। क्योंकि यह एक बिना लाइसेंस वाले टेराहर्ट्ज स्पेक्ट्रम का उपयोग करता है, रेडियो फ्रीक्वेंसी के लिए प्रतिरोधी है, और स्थापित करने के लिए अधिक सुरक्षित है, IEEE 802.15.7 मानक OWC को एक समाधान के रूप में पेश करता है। हालांकि, मानक सेंसर अनुकूली डेटा आवश्यकताओं या प्राथमिकता डेटा ट्रांसमिशन को संबोधित नहीं करता है, जो सेवा आवश्यकताओं की महत्वपूर्ण गुणवत्ता है। हमारा नियोजित शोध विलंबता, अनुकूली यातायात प्रबंधन और वायरलेस सेंसर के समग्र नेटवर्क थ्रूपुट पर केंद्रित है क्योंकि वे व्यक्तिगत चिकित्सा स्वास्थ्य देखभाल में तेजी से व्यापक हो जाते हैं। हमने अनुकूली डेटा प्रबंधन स्लीप मोड की अनुमति देते हुए एक अद्वितीय सुपरफ्रेम संरचना का प्रदर्शन किया। विवाद पहुंच अवधि (सीएपी) और विवाद मुक्त समय दोनों के लिए, प्रस्तावित सुपरफ्रेम संरचना सिम्युलेटेड (सीएफपी) है। प्रस्तावित तकनीक एक हाइब्रिड मोड में संचालित होती है, जिसमें कैरियर सेंस मल्टीपल एक्सेस (सीएसएमए/सीए) और जीटीएस आवंटन एल्गोरिदम का संयोजन होता है। IEEE 802.15.7 से इसकी तुलना करके, हमने विलंबता और

थ्रूपुट में हमारे प्रस्तावित कार्य के महत्व का प्रदर्शन किया। सिमुलेशन परिणामों के अनुसार, दोनों घटकों में बहुत सुधार हुआ है। इसके अलावा, हमारे प्रस्तावित अनुकूली सुपरफ्रेम संरचना की टक्कर की संभावना की गणना की गई थी।

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List of Acronyms

A

AR	Augmented Reality
AI	Artificial Intelligence

B

BER	Bit Error Rate
BLE	Bluetooth Low Energy
BO	Beacon Order
BSFD	Base Superframe Duration
BI	Beacon Interval
BE	Beacon Exponent
BSN	Bio-Sensor Network

C

CSK	Colour Shift Keying
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CAP	Contention Access Period
CFP	Contention Free Period
CCA	Clear Channel Assessment
CAGR	Compound Annual Growth Rate
CB	Contingency Beacon
CT	Contingency Traffic
CTS	Clear-to-Send
CC	Convolutional Codes
CDR	Clock and Data Recovery

D

DC	Data Centre
DTMC	Discrete Time Markov Chain
DSME	Deterministic and Synchronous Multichannel Extension
DCF	Distributed Coordination Function

E

ECG	Electro Cardiogram
EEG	Electroencephalogram

F

FoV	Field of View
FSO	Free Space Optics

FSOI	Free Space Optics Interconnects
FCS	Frame Check Sequence

G

GTS	Guaranteed Time Slots
Giga-IR	Gigabit- Infra Red

H

HetNets	Heterogeneous Networks

I

ICT	Information and Communication Technology
IR	Infra-Red
IoT	Internet of Things
IS-OWC	Inter-Satellite Optical Wireless Communication
IDC	International Data Corporations
ISP	Internet Service Provider

L

LoS	Line of Sight
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of Radiations
LAN	Local Area Network
LiFi	Light Fidelity
LDPC	Low Density Parity Check

M

MAC	Media Access Control
M2M	Machine to Machine
MHR	MAC Header
MFR	MAC Footer
MFTP	Maximum Flicker Time Period

N

NB	Number of Backoff

O

OWC	Optical Wireless Communication
O-NoC	Optical Network on Chip
OCC	Optical Camera Communication
OWPAN	Optical Wireless Personal Area Network
OOK	On-Off Shift Keying

OFDM	Orthogonal Frequency Division Multiplexing

P

PHY	Physical
P2P	Point to Point
PB	Priority Beacon
Ph2Ph	Phone to Phone

Q

QoS	Quality of Service

R

RF	Radio Frequency
RT	Regular Traffic
RTS	Request-to-Send

S

SNR	Signal to Noise Ratio
SoC	System on Chip
SO	Superframe Order
SD	Superframe Duration
SARS-CoV	Severe Acute Respiratory Syndrome Corona Virus
RS	Reed_Solomon

T

TG4	Task Group 4
TDMA	Time Division Multiple Access
TTRC	Time To Report Contingency

U

UVC	Ultra Violet Communication
UGAS	Unbalanced GTS allocation Scheme

V

VLC	Visible Light Communication
V2V	Vehicle to Vehicle
VPPM	Variable Pulse Position Modulation
VM	Virtual Machine
VPAN	Visible Light Communication-Personal Area Network
V2I	Vehicle-to-Infrastructure

W

WBAN	Wireless Body Area Network

WiFi	Wireless Fidelity
WMAN	Wireless Metropolitan Area Network
WuR	Wake up Radio
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Networks
WPAN	Wireless Personal Area Network

List of Symbols

α	Probability of sensing the channel busy during CCA1
β	Probability of assessing the channel busy during CCA1
τ	Probability of failure in each of the back-off stage
Φ	Probability that a node spends a randomly chosen time-slot in CCA
$\beta_{Acknowledgement}$	Probability of getting medium busy by device N during slot c^2
$b_{x,z}$	Steady state probability for s(t) = x and c(t) = z
CFP_{G1}	Optional adaptive CFP part for GTS-based transmissions
CFP_{G2}	Standard CFP duration for GTS-based transmissions
CAP_1	Contention access period duration one
CAP_2	Contention access period duration two
C_t	Total count of instances in which more than one node tries to sense the channel at the exact moment
D_{Std}	Average transmission delay according to the standard
D_{Prop}	Average transmission delay according to the proposed scheme
D_{SCAP}	Delay for CAP-based transmission in CAP_1 according to standard
$D_{PCAP\ (1)}$	Delay for CAP-based transmission in CAP_1 according to the proposed scheme

$D_{PGTS,PD}$	Delay for a priority data packet to be transmitted in CFP_{G1}
$D_{PGTS(1),PD(w)}$	Worst case delay for the proposed scheme
E_{Std}	Average energy consumption according to the standard
E_{Prop}	Average energy consumption according to the proposed scheme
$E2E$	End-to-End epoch
F_t	Total number of failed attempts
L_p	Packet transmission duration in slots
L_c	Time wasted in waiting for Ack
L_a	Acknowledgement packet length
N	Number of devices in the network
N_{GTS}	Number of GTS slots needed to send the packets
N_b	Utmost unit of data of bits that can be fitted in one GTS
P_i	Amount of data to be communicated
P_{coll}	Likelihood of network collision
P_r	Amount of power consumed during reception
P_t	Amount of power consumed while transmission
P_i	Amount of power consumed during sleep mode
P_d	Packet drop probability
P_{Nc}	Network collision probability
P_{Tx}^{N-k}	Probability of transmission by any other node other than k nodes at a particular slot
P_c	Probability of collisions among nodes
S_0	Per-node throughput

s(t)	Random state variable representing backoff counter status
S_t	Total number of successful attempts
T_{BO}	Backoff time duration
T_{data}	Data packet size
$T_{PHY\ header}$	Physical layer header size
$T_{MAC\ header}$	MAC layer header size
$T_{packet\ size}$	Payload
T_{IFS}	Interframe spacing
T_{ack}	Acknowledgment transmission duration
T_{SIFS}	Short IFS duration
$T_{transmission}$	Overall transmission time for a data packet
T_{beacon}	Beacon transmission duration
T_{IP}	Inactive period duration
T_{TTRC}	Time to report contingency duration
T_{total}	Time required to transmit the required count of packets
T_{GTS}	Duration of one GTS
U_{PD}	Link utilization for data transmission with priority GTS in CFP_{G1}
U_{ND}	Link utilization for normal data transmission under GTS allocation in CFP_{G2}
U_i	Link utilization for i^{th} node
W_x	Size of contention window